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CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Development and Testing of Plastic Lumber Materials for Construction Applications

by
Richard G. Lampo and Thomas J. Nosker

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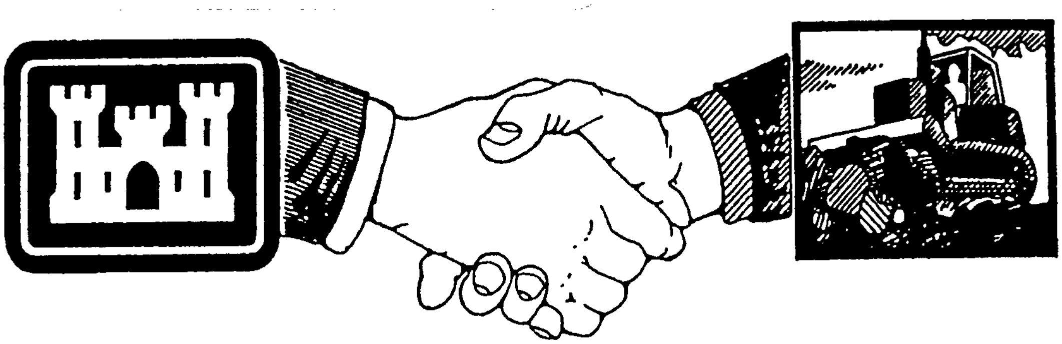

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13. ABSTRACT (Maximum 200 words)

Commingled post-consumer waste plastics are virtually worthless as recycling stock. Most waste plastics are landfilled, but U.S. landfill space is growing scarce and disposal costs are continually rising. One way to control disposal costs and waste volumes is to develop new products from plastic wastes. Some products of this type — construction materials called plastic lumber — have already reached the commercial market. Plastic lumber has some advantages over wood (e.g., it resists rot and insect attack), but its mechanical properties differ significantly from wood. A lack of technical information and design guidance have slowed construction industry adoption of plastic lumber.

Research was conducted to develop plastic lumber stock from mixed waste plastics and verify its performance in select applications. It was found that (1) the compressive strength of the stock tested was equal or superior to wood, (2) the stiffness of plastic lumber is at least an order of magnitude lower than even the softest woods, and (3) plastic lumber is subject to much higher levels of creep than wood.

Draft test methods, material specifications, and usage/design guidance developed in this work have been adopted by the American Society for Testing and Materials as industry standards.

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Foreword

This study was conducted for Headquarters, U.S. Army Corps of Engineers under Construction Productivity Advancement Research (CPAR) Work Unit LQ1, "Developing Construction Materials From Commingled Waste Plastics." The technical monitor was D. Chen, Directorate of Military Programs (CEMP-ET).

The work was performed through a Cooperative Research and Development Agreement (CPAR-CRDA) between the Materials Science and Technologies Division (FL-M) of the Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL) and the Center for Plastics Recycling Research* at Rutgers University, New Brunswick, NJ. The USACERL Principal Investigator was Richard G. Lampo, CECER-FL-M, and the Rutgers University Principal investigator was Dr. Thomas J. Nosker. Dr. Ilker R. Adiguzel is Acting Chief, CECER-FL-M, and Donald F. Fournier is Acting Operations Chief, CECER-FL. The USACERL technical editor was Gordon L. Cohen, Technical Information Team.

Dr. Michael J. O'Connor is the Director of USACERL.

* This unit is now called the Plastics and Composites Group, Department of Civil and Environmental Engineering, Rutgers University.

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1 Introduction

Background

Over 8.4 billion pounds of rigid plastic containers are produced annually in the United States (Modern Plastics 1994). Potentially, this entire quantity could end up in landfills. To divert at least some of these post-consumer waste plastics from landfills, many communities have initiated recycling programs. Given present technology, only unpigmented, high-density polyethylene (HDPE) milk jugs and polyethylene terephthalate (PET) soda bottles can economically be recovered and recycled into new containers. (The milk jugs and soda bottles are easily recognized by their size and shape, making them easy to separate from the mixed waste stream.) Even if all available HDPE milk jugs and PET soda bottles were recycled, over 6 billion pounds of mixed waste plastics would still end up in landfills. These mixed (commingled) waste plastics are sometimes referred to as "curbside tailings" (see Figure 1*). Curbside tailings typically have a negative value; the materials are worth less than the cost of landfilling them. Because U.S. landfills are filling rapidly, and new ones are increasingly difficult to establish due to environmental restrictions and public opinion, waste disposal costs are constantly rising. To control these costs and reduce the amount of wasted plastic, researchers and entrepreneurs have begun to develop new ways to reuse this waste material. One promising solution is to take advantage of curbside tailings as a new, inexpensive raw feedstock material for the fabrication of alternative construction materials. Some companies have begun producing recycled plastic building materials in typical stock lumber dimensions for use as wood substitutes. These materials are now commonly referred to as *plastic lumber*.

Although the currently available plastic lumber materials offer some advantages over wood (e.g., natural resistance to rot and insect attack), plastic lumber has mechanical properties much different than those of wood. Consequently, the industry acceptance of plastic lumber for construction applications has not been as rapid or widespread as originally hoped. Major barriers to industry acceptance are the lack of understanding of the property differences and the lack of material specifications and design guidance.

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* Figures and tables are located at the end of their associated chapters.

To more widely demonstrate the technology and to promote technology transfer and commercialization, the Center for Plastics Recycling Research (CPRR) at Rutgers University submitted a proposal to the U.S. Army Corps of Engineers Construction Productivity Advancement Research (CPAR) Program to develop construction materials from commingled (mixed) waste plastics. (Appendix A gives further information on the CPAR Program.) A CPAR project was approved for execution beginning in 1992 to develop and evaluate the performance of plastic lumber products for construction applications. The industry/academic CPAR partner for this project was Rutgers University, New Brunswick, NJ. The laboratory partner was the U.S. Army Construction Engineering Research Laboratories (USACERL), Champaign, IL. Partner participants included a consortium of 11 manufacturers of plastic lumber and timber products as follows:

- Aeolian Enterprises
  Latrobe, PA 15650
- Amoco Fabrics and Fibers Company
  Atlanta, GA 30339
- ARW Polywood, Inc.
  Lima, OH 45802
- Bedford Industries, Inc.
  Worthington, MN 56187
- Duratech Industries
  Lake Odessa, MI 48849
- Eaglebrook Products, Inc.
  Chicago, IL 60608
- Earth Care Products, Inc.
  Boca Raton, FL 33431
- Partek Corp.
  Vancouver, WA 98666
- The Plastic Lumber Company, Inc.
  Akron, OH 44311
- Superwood of Alabama
  Selma, AL 36702
- Trimax of Long Island
  Ronkonoma, NY 11779

Objectives

The objective of this project was to develop and verify performance of construction materials made from recycled commingled waste plastics, including timber piles, sheet piling, sheathing (flat stock), beams, columns, and siding. Draft test methods, material specifications, and usage/design guidance were developed and submitted to the American Society for Testing and Materials (ASTM) for adoption as industry standards.

Approach

The initial step in this project was to coordinate all participant manufacturers and survey types and sizes of plastic lumber products they produce using post-consumer waste plastics. The researchers selected 2 x 4 boards and 4 x 4 timbers for property evaluations and comparisons. Mechanical testing was conducted to evaluate the compressive and creep properties of the products.

Documented applications of plastic lumber materials were surveyed. Successful and unsuccessful applications were reviewed. Using the laboratory test data on mechanical properties and any performance history and design information that could be found, several demonstration structures were designed. Due to budget and project time constraints, not all of the designed structures could be built.

As discussed further in Chapter 7, draft test methods, specifications, and standards for plastic lumber were prepared and submitted for consideration by a new ASTM committee section on plastic lumber and shapes (Section D20.20.01).

Technical papers on this project were written and presented at conferences and symposia. Specific references are presented in Chapter 7.

Scope

The original project objectives, as stated above, specified timber piles, sheet piling, flat stock, and siding as products to be included in this study. Although most of the information developed under this project would apply to those products as well, a more accurate description of the product focus is *plastic lumber*.

The current draft ASTM terminology defines plastic lumber as "a manufactured product composed of more than 50 weight percent resin, in which the product generally is rectangular in cross-section and typically supplied in board and dimensional lumber sizes, may be filled or unfilled, and may be composed of single or multiple resin blends" (ASTM 1996). This definition would encompass timber piles as dimensional timbers and sheet piling and siding as tongue-and-groove plastic lumber products. However, very large (e.g., 50-70 foot long by 13 in. diameter) fender and load-bearing structural piles for marine applications and heavy-duty sheet piling were beyond the scope and resources of this CPAR project.

As part of the Fiscal Year 91 CPAR Program, a project was initiated, with a specific focus on plastic composite piling systems for marine applications. Also, when

looking at different applications for plastic lumber under this CPAR project, a preliminary investigation was conducted to its potential use as railroad crossties. However, after this preliminary investigation, it was determined that the development of plastic railroad crossties would be beyond the original scope and available resources of this CPAR project. As evidence of the high interest and potential for recycled plastics in this application, however, Rutgers University entered into a cooperative program with two major railroads (Conrail and Norfolk Southern) and a plastic lumber manufacturer (Earth Care Products, Inc.) to develop and test RR crossties made from reinforced recycled plastics. Considering the 2,200 plus miles of track on Army installations and the maintenance needs of wood ties, USACERL is also participating in the railroad tie project under non-CPAR funding as provided by Headquarters, U.S. Army Corps of Engineers.

Metric Conversion Factors

This reports uses U.S. standard units of weight and measure. A table of conversion factors for standard international (SI) units is provided below.

1 ft	=	0.305 m
1 mi	=	1.61 km
1 lb	=	0.453 kg
1 sq in.	=	$6.45 \times 10^{-4} m^2$
1 psi	=	6.895 kPa
1 plf	=	14.59 N/m
1 lbf	=	4.448 N

Figure 1. "Curbside tailings"—mixture of containers after removing plastic milk jugs and soda bottles.

2 Review of Plastics Recycling and Plastic Lumber Applications

Introduction

The earliest records of plastic lumber used in the public domain date back to the early 1970s, when plastic lumber processes were developed in Europe and Japan, and U.S. patents were applied for. At that time, the materials targeted for processing into plastic lumber consisted solely of post-industrial plastic scrap, which was the only source of low-priced plastic available at that time. These industries did not experience rapid growth, and in fact disappeared altogether in Japan.

In the late 1980s, plastic lumber processes were considered by recycling experts as a possible processing alternative to landfilling for mixed waste plastics, a byproduct of recycling systems that target specific recyclable resin packages. The economic and logistical need to reduce disposal quantities is now driving the commercial viability of this new industry in the United States.

Raw Materials and Sources

To evaluate the current possibilities for the recycling of post-consumer plastic wastes, it is first necessary to identify which types of material are both available and collectible from the municipal solid waste (MSW) stream. Of the major nonfibrous plastics used in the United States, Table 1 shows that plastic packaging—generally comprising products with a short useful lifetime—is the end-use category with the greatest contribution by weight. At about 18 billion pounds per year, plastic packaging is about 3 percent by weight (and under 10 percent by volume) of the 500 billion pounds per year attributed to the total MSW stream (Nosker, Rankin, and Morrow 1989).

While the expected useful lifetime for most plastic packaging is short and it ultimately enters the waste stream, only those items that are readily collectible can be recycled effectively. As Table 2 shows, plastic containers—the major target of community recycling collection programs—currently constitute about 8.4 billion pounds, or approximately half of all plastic packaging wastes. Most of these

containers are readily collectible, processable, and salable, and, they also can serve as feedstocks for a large number of reclamation businesses. The approximately 7 billion pounds of plastic films used in packaging are also reclaimable and reusable, but they are in fact relatively difficult to recycle because the required infrastructures are not yet in place. An analysis of plastic container types and their constituent polymers is useful in identifying a viable feedstock for the production of products made from recycled plastic wastes.

Of the different types of plastics used in rigid containers in the United States (Table 3), high density polyethylene (HDPE) and polyethylene terephthalate (PET), molded into milk jugs and beverage bottles, respectively, are the most easily identified. Because these materials have high inherent value, they are prime targets for recycling. In 1993, 450 million pounds of PET bottles were recycled in resin-recovery systems, for a 28.6 percent recycling rate. The great majority of this material was recovered in the form of soft drink bottles, and it produces the highest recycling rate for any plastic packaging material (Waste Age 1994). Un-pigmented HDPE from milk containers is recycled at a lower (but increasing) rate. The largest percentage changes in plastics used for rigid containers between 1990 and 1993 are the increase of PET and the decrease of polyvinyl chloride (PVC). This change is attributable to the success of PET recycling as well as the commercial advantage that results from the perceived environmental benefits associated with switching to a highly recyclable material. The major current problem in plastics recycling is getting more waste plastic containers collected, sorted, and placed into the existing reuse infrastructure. Though many states and communities are initiating programs to collect these materials, the increase in recycling rates has been slowed by the inherent inefficiencies in obtaining well-sorted bottles for resin recovery processes, which make resin recovery relatively expensive. Bottles collected for PET and HDPE resin-recovery processes are typically hand-sorted from other recyclables at a materials recovery facility, baled, shipped to a resin-recovery plant, unbaled, resorted, then granulated. Nevertheless, regardless of the increased success in recycling a select portion of plastic containers as individual generic cleaned resins, little progress has been made in reducing the amount of plastic that ends up in landfills. Fortunately for the purposes of recycling, the remaining commingled plastic wastes can be processed into lumber profiles and other useful products. In the United States there are approximately 30 companies that manufacture plastic lumber using some post-industrial or post-consumer plastic scrap. Increasing the ability of industry to use commingled waste plastics in these products would help to relieve the nation's growing waste disposal problem.

Plastics Available Through the Solid Waste Stream

Commingled plastics processes can use many feedstocks, including post-consumer waste plastics, industrial scraps, filler materials, and other additives. Rigid plastic containers provide the most widely available and readily collectible source of post-consumer waste plastics.

Apart from the examples noted above (i.e., unpigmented milk jugs and soft drink bottles), most plastic containers are not standardized for a particular packaged product. Containers for household cleaners, cooking oils, foods, motor oils, etc., may vary widely in shape, color, and composition depending on the manufacturer (see Table 4). Sometimes manufacturers even change the polymer blend used in a specific package without notice. These factors make it difficult and expensive to sort waste plastic packaging, even when they are marked with the industry-standard resin codes. Furthermore, any given resin may be produced in a variety of colors, greatly compounding the sorting problem. Consequently, the mixed plastic containers left after the removal of HDPE milk jugs and PET soda bottles are typically either sent directly to a landfill or used by a commingled plastics processor to produce salable articles. For purposes of brevity, these remaining mixed plastics will be referred to hereinafter as *tailings*.

Collection and Sorting

At the present time, most plastics recyclers accept only unpigmented HDPE milk and water jugs and PET soda bottles. These two materials comprise 80 percent of the plastics that people place at curbside for recycling leaving 20 percent as a potential commingled feedstock. These materials are generally hauled with all other recyclables to a materials recovery facility (MRF). The plastics are separated into three categories: (1) unpigmented HDPE, (2) clear and green PET, and (3) the tailings. It is estimated that approximately 6.4 billion pounds of rigid plastic tailings are potentially available for reclamation in the United States each year.

The exact polymeric composition of the tailings, which consist principally of polyolefins, vary from one municipality to another and from year to year as collection and sorting practices change. The CPRR estimated that tailings received from central New Jersey during the mid to late 1980s consisted predominantly of HDPE (about 80 percent) with small amounts of other thermoplastics (see Table 5 [Applebaum et al. 1990], and Table 18 [E.B. Nauman, Rensselaer Polytechnic Institute, private communication, 1990]).

Additional commingled waste plastics are readily formed by the blending of plant scraps, recycled thermoplastics, or fillers either with each other or with curbside tailings.

Manufacturing Processes

Several types of manufacturing processes have been developed specifically for processing bulky items from commingled plastics. These processes may be roughly categorized into four basic types:

1. intrusion processes based on Klobbie's design
2. continuous extrusion
3. the Reverzer process
4. compression molding.

Each process is capable of producing products from a variety of macroscopically inhomogeneous mixtures of waste plastics, all containing some degree of contamination. Because of the heterogenous nature of these mixtures, commingled processes are limited to producing products of large cross section, where small internal imperfections may be of little consequence to the mechanical properties. Properties are measured by testing several large samples, thereby averaging the effects due to the inclusions or process-related voids upon the bulk material. Experiments using different combinations of commingled plastics as feedstocks have been found to yield properties heavily dependent upon feedstock composition.

Klobbie-Based "Intrusion" Processes

In the 1970s, Eduard Klobbie of the Netherlands began developing a system for processing "unsorted thermoplastic synthetic resin waste material into an article having the working and processing properties of wood" (Klobbie 1974). His system consisted of an extruder, several long, linear molds of large cross-section mounted on a rotating turret, and a tank of cooling water into which the turret was partially submerged. The process is reviewed here briefly, but more detail can be obtained from Klobbie (1974), Leidner (1981), and *REHSIF Bulletin* No. 400.

The extruder first works and softens the thermoplastic mixture, and then forces the material into one of the molds without using a screen-pack or extrusion nozzle. After the mold has been filled, the turret rotates one position in order to fill the next mold. Eventually, each mold slowly passes underneath the coolant level in the tank, where the plastic cools, solidifies, and shrinks away from the mold, allowing

coolant into the gap between the product and mold surface. After the turret is further rotated to raise the cooled molds from the liquid, the finished parts are removed from the molds. This process is a cross between conventional injection molding and extrusion, and therefore may be termed an intrusion process. Klobbie never patented his system in the United States, but he did patent the use of foaming agents in such equipment (Klobbie 1974). This process can use a very wide variety of feedstocks as long as sufficient structural integrity is built into the molding system.

Several companies worldwide currently produce and utilize systems for processing mixed plastics waste similar to Klobbie's original machine. These machines are capable of making objects where the length is high compared to the cross-sectional area, such as posts, poles, stakes, planks, and slats.

Continuous Extrusion

A variation of the Klobbie technique that may be used to produce linear profiles from mixed plastic waste involves continuous extrusion. This process, used to extrude materials of large cross-section into cooled dies, works in a manner similar to continuous pipe manufacture. There are special considerations when adapting this technology to large profiles made from commingled plastic waste. For example, provisions must be made to cool the extruded material for a fairly long time because of the large cross-sections produced. Polymers generally have low thermal conductivity, so large profiles exhibit considerable temperature gradients between the interior and the outer skin during cooling. Another important consideration is raw material consistency in terms of melt index and other rheological properties. A lack of material consistency could result in surging and a lack of dimensional stability for the product.

The advantage of this process is that the extruder operates continuously and foamed materials are easy to facilitate, as are hollow or multilayer profiles. In addition, product length is limited mainly by the size of the manufacturing facility.

Several companies are developing and marketing continuous extrusion equipment designed for use with commingled plastics. These systems typically use vacuum calibration devices to control final product shape.

The Reverzer

The earliest process for fabricating products of large cross section from commingled plastics patented in the United States was developed by Mitsubishi Petrochemical.

The process, called the *Reverzer* process, is described in *Polymer Age* (1974), *REHSIF Bulletin* No. 300, and Leidner (1981).

In this process, commingled waste plastics are softened in a hopper, and then screw-mixed to develop a well-blended uniform batch of fluidized plastic. There are three systems for transforming the output of the Reverzer into useful products: (1) flow molding, (2) extrusion, and (3) compression molding. In flow molding, molten plastic is fed under very low pressure into thin molds made of sheet metal. The extrusion system allows the machine to operate as a low-pressure extruder, generally filling long linear molds. Adaptation to compression molding makes use of a special device to develop the high pressures necessary for filling large molds of sizable surface area. The Reverzer process is capable of producing many different shaped items from commingled plastic wastes, and is not limited to linear shapes as are the Klobbie and continuous extension processes. The Reverzer process is also extremely versatile in that it is capable of accepting a large variety of mixtures of contaminated commingled scrap as feedstock.

Mitsubishi apparently did not achieve marketing success with this equipment, however. Manufacture of the Reverzer was terminated after only 8 units were produced.

Compression Molding

The most successful technology for the compression molding of commingled plastics was developed in the Federal Republic of Germany by Erich Weichenreider, and is called Recycloplast (Brewer 1987). This process mixes batches consisting of 50–70 percent thermoplastics with other materials, melting via friction the portions of the mix characterized by low melting points. An automatically adjusted scraper then removes the melted material from the plasticator and presses it via a heated extruder die into premeasured, roll-shaped loaves. The loaves are then conveyed to a press-charging device, which fills a sequence of compression molds alternately. Products are cooled in the molds to a temperature of 40 °C and ejected onto a conveyor that carries the product to a storage area. Flashing from the mold process may be transferred to a granulator for in-house recycling. One of the major differences between this process and those discussed previously is that plant size is necessarily large, so the capital investment is large by comparison. Alternatively, this process has high throughput, and is capable of producing finished thick-walled products such as pallets, grates, benches, and composting boxes.

Commingled processes such as those discussed here generally are dedicated to the fabrication of bulky products that in many cases are candidates as substitutes for

wood products, to be used in applications where physical properties are widely assumed not to be critical. For commingled plastic products to substitute for wood over a variety of even more critical applications, it is reasonable and desirable that the products have mechanical properties that approach those of wood. While good mechanical properties are important, purely economic considerations may be somewhat less important if there are compelling advantages to using plastics, such as superior resistance to environmental stresses.

Economic data for these commingled processes are readily available. The cost range for processing plastic lumber is estimated to be $0.19 to $0.25 per pound (J. Macako, "The Economics of the ET-I Operation," presentation, 23 March 1990). This translates into a cost-per-unit-length about twice that for pressure-treated lumber. On the other hand, there is the issue of environmental impact—specifically the comparative effects of pressure-treated lumber versus commingled plastic products upon aquatic ecosystems (Weis et al. 1992).

Data on the mechanical properties of commingled materials is much scarcer. This reflects in part the hesitation of the scientific community—academic and industrial—to mechanically test commingled products and to study blends. Scientists were aware of the commercial significance of the mechanical blending of mixed plastics waste (Traugott, Barlow, and Paul 1983), but they dedicated their studies to blends made from virgin polymers rather than recycled resins. Ostensibly, by understanding more fully the processing of well characterized polymer pairs (and their resultant properties and morphologies), such information would promote the commercial blending of mixed plastic wastes. However, as a result of some very interesting and thorough studies (Fayt, Merome, and Teyssie 1981; Lindsay, Paul, and Barrow 1981), most polymer scientists remain convinced that it is fruitless to try making useful products from mixtures of incompatible plastics (Elias 1984), such as those commonly used by the packaging industry.

Nevertheless, this conventional wisdom among plastics scientists is contradicted by other studies and actual practice: good and consistent properties *can* be obtained for commingled products made from post-consumer plastic wastes.

Review of Current Plastic Lumber Applications

Some of the first uses for plastic lumber were for traditionally wooden items like park benches and picnic tables, which are subject to degradation by constant environmental exposure, the effects of mold, etc. (Figures 2 and 3). Note the support block midway under the picnic table seat (Figure 3). This support block implies that

these plastic materials have different mechanical properties than wood. Figures 4, 5, and 6 show newer, commercially produced picnic tables and benches made from recycled plastics. The need for the support block (Figure 3) has been eliminated by a reduction in the span distance between the legs, or the piece has been replaced with other forms of reinforcement not obvious from a top view. While the use of plastic lumber to make such small-scale products is completely appropriate, using commingled tailings in layer load-bearing and structural applications would consume much greater volumes of waste plastics.

With its inherent resistance to rot and insect attack, plastic lumber has in fact been used as a replacement for chemically treated woods in various larger-scale outdoor applications. Figure 7 shows a boardwalk made with plastic lumber decking and Figure 8 shows a boat slip made with plastic lumber decking. These examples show some of the more successful applications of plastic lumber in engineering structures, but there also have been some unsuccessful applications.

In most cases, unsuccessful application of plastic lumber arises from a lack of understanding of the differences in mechanical property between plastic lumber and wood. Although plastic lumber is produced in common dimensional lumber sizes, plastic lumber generally is *not* appropriate for direct substitution for wood of similar dimensions. This is especially true for load-bearing applications. Substitution can produce structures that have unacceptable deflections under load or that will sag with time—sometimes even under its own weight. Successful plastic lumber decking applications, for example, usually require either that the spacing between joists is closer together, or that boards are larger in cross-sectional thickness than the normally specified wood decking boards. Also noteworthy is that plastic lumber structures often incorporate natural wood for load-bearing members such as column, beams, and joists.

In attempts to alter mechanical properties or to use other non-polymeric waste materials, some plastic lumber manufacturers have incorporated particles and fibers into the matrix. The addition of short glass fibers can significantly increase the elastic modulus (stiffness) of plastic lumber (although still not to the levels of wood, as discussed in Chapters 3 and 4). Furthermore, the addition of fibrous materials to plastic lumber stock has caused performance problems in some exposures. Figure 9 shows two boards (of different size cross-section) made from recycled plastics and wood. The sample on the right has not been exposed to the elements. The sample on the left, however, shows the same type of board after being exposed to splash zone conditions for less than 1 year (the board is from an actual site installation). Failure probably occurred because the wood fibers, along with the high percentage of low-

density polyethylene in the product, rapidly deteriorated under the direct sunlight and continuous dampness.

Two other issues that must be addressed in plastic lumber applications are (1) the materials heat-retention properties and (2) its capacity to irritate skin with which it comes into contact.

Plastic lumber gets very hot in direct sunlight and does not cool off very fast. This is not surprising since the plastic matrix has a high heat capacity and is a good insulator. Consequently, the material is slow to absorb heat and slow to radiate it. Providing a small gap between adjacent boards will allow some air movement around the boards and provide some cooling effect.

In some cases it has been reported that people experience itching after coming into contact with plastic lumber boards that contain embedded glass fibers. This problem is probably most evident on new structures before the exposed glass fibers are washed or worn away. To eliminate the problem, members that may touch a person's skin (such as decking, railings, and seating) should not contain chopped glass fibers or other potential irritants.

Table 1. Major nonfibrous plastics uses (millions of lb).

Plastics Use	1992	1993
Packaging	16,519	17,338
Building	11,414	12,764
Transportation	2,475	2,406
Appliances	1,346	1,479
Electrical/Electronic	1,975	2,072
Furniture	1,143	1,289
Toys	846	921
Housewares	1,546	1,600

Source: *Modern Plastics*, 1994.

Table 2. Plastics in packaging by end-use (1993).

Polymer End-Use	Percent	Millions of Pounds
Containers	48.3	8,380
Film	38.9	6,743
Coatings	7.1	1,227
Closures	5.7	988
Total*	100	17,338

*Does not include adhesives.
Source: *Modern Plastics*, 1994.

Table 3. Plastics used in rigid containers.

Material	1990 Percent (10^6 lb)	1993 Percent (10^6 lb)
polyethylene (PE)	53.4 (3,430)	52.9 (4,434)
polyester (PET)	12.1 (780)	20.8 (1,744)
polystyrene (PS)	15.6 (1,000)	15.5 (1,298)
polypropylene (PP)	6.9 (440)	6.4 (536)
polyvinyl chloride (PVC)	5.1 (330)	2.7 (143)
Other	6.9 (440)	1.7 (143)
Total	100 (6,420)	100 (8,380)

Source: *Modern Plastics*, 1994.

Table 4. Composition of all-plastics recycling stream on 31 January 1992, Somerset, NJ.

Type	As Collected	CT*
PET soda	25.7	--
HDPE, non-milk	48.3	90.2
HDPE, milk/water	20.8	--
PVC	1.7	3.2
PET, non-soda	2.4	4.5
PP	0.3	0.5
Other (#7)	0.9	1.6
LDPE	--	--
PS	--	--

*Curbside tailings as collected with PET soda and HDPE milk/water removed.

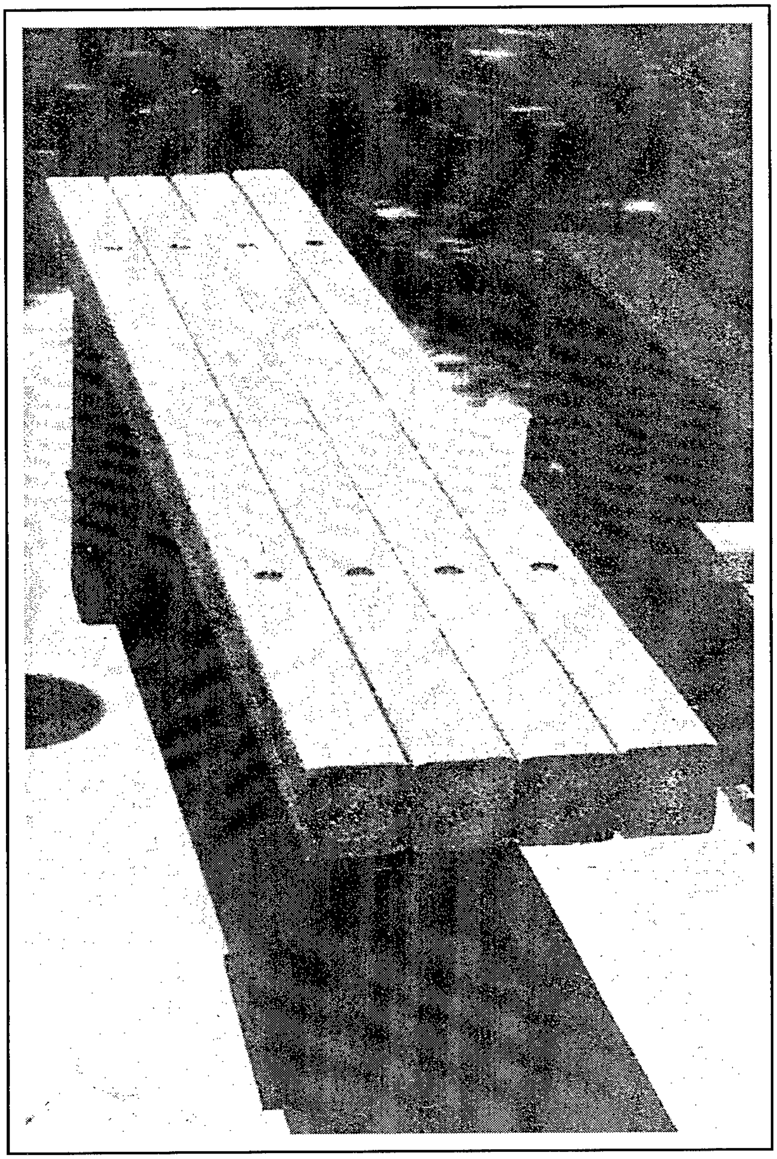

Figure 2. Park bench made from recycled plastics.

Figure 3. Plastic lumber picnic table. Note the support block midspan under the seat.

Figure 4. Commercially produced plastic lumber benches.

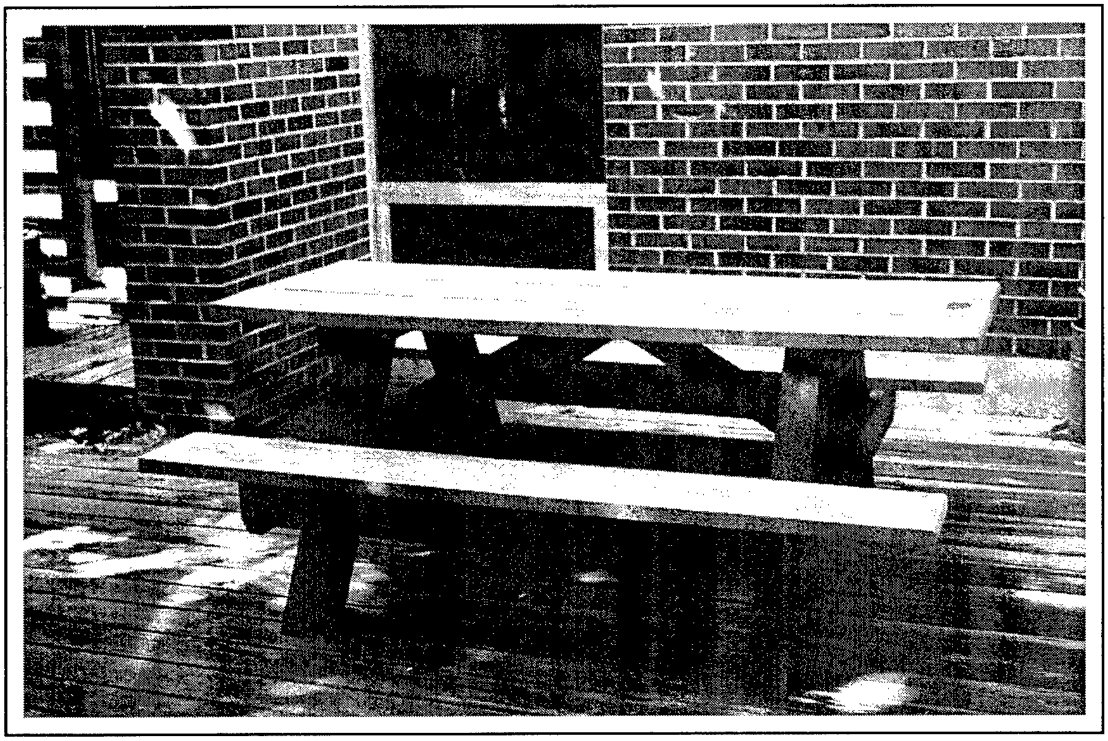

Figure 5. Commercially produced plastic lumber picnic table.

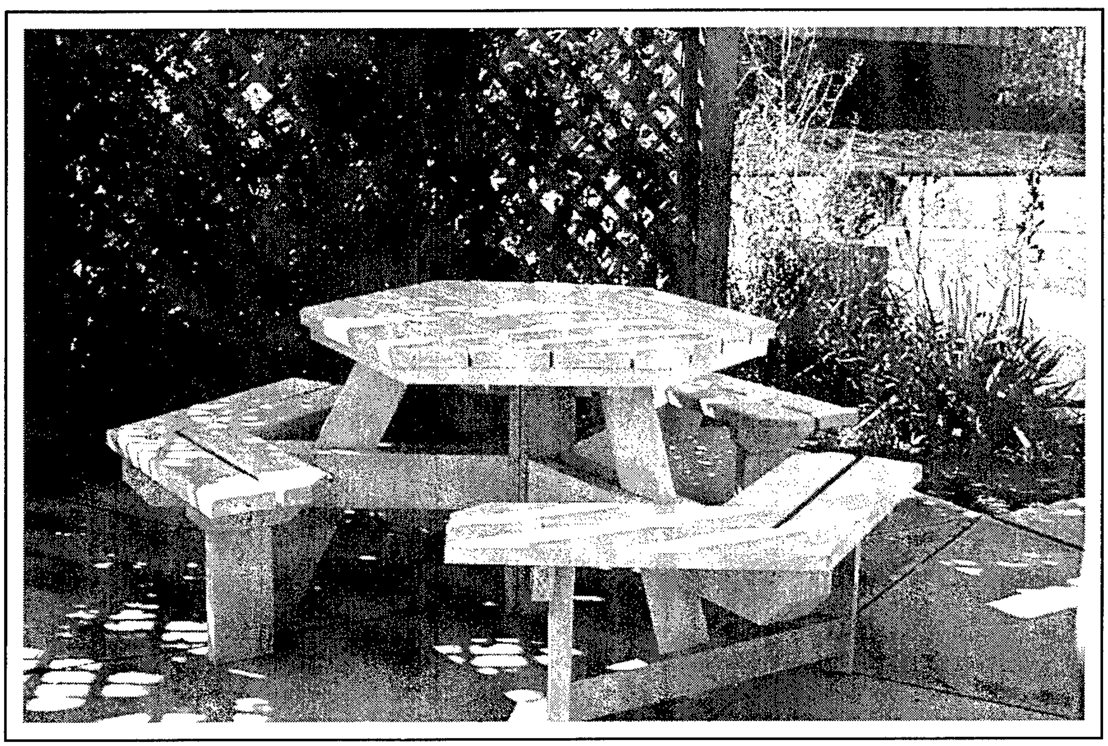

Figure 6. Hexagon-shaped plastic lumber picnic table.

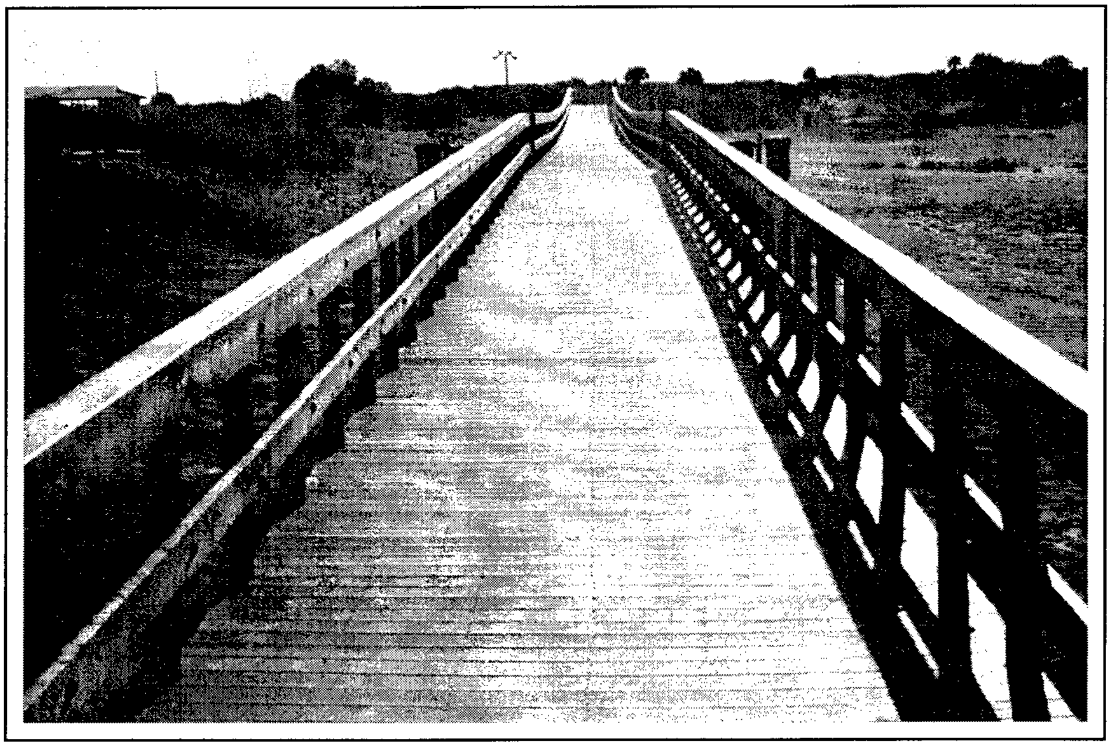

Figure 7. Boardwalk made using plastic lumber decking boards.

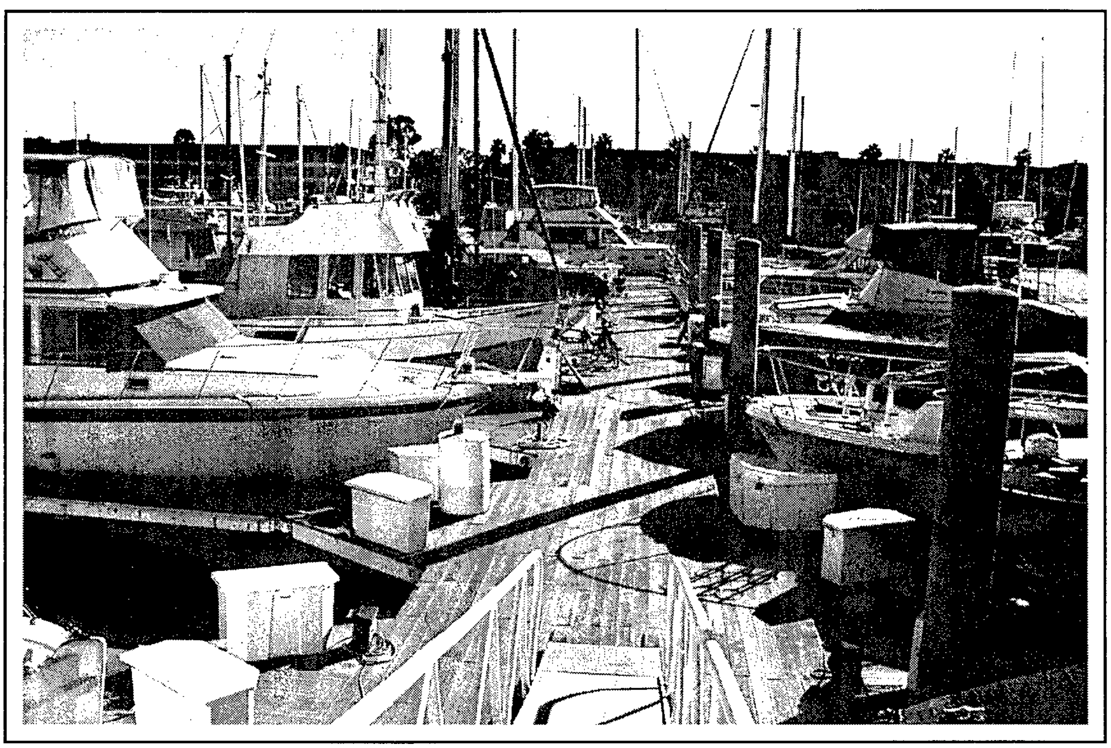

Figure 8. Boat slip made with plastic lumber decking.

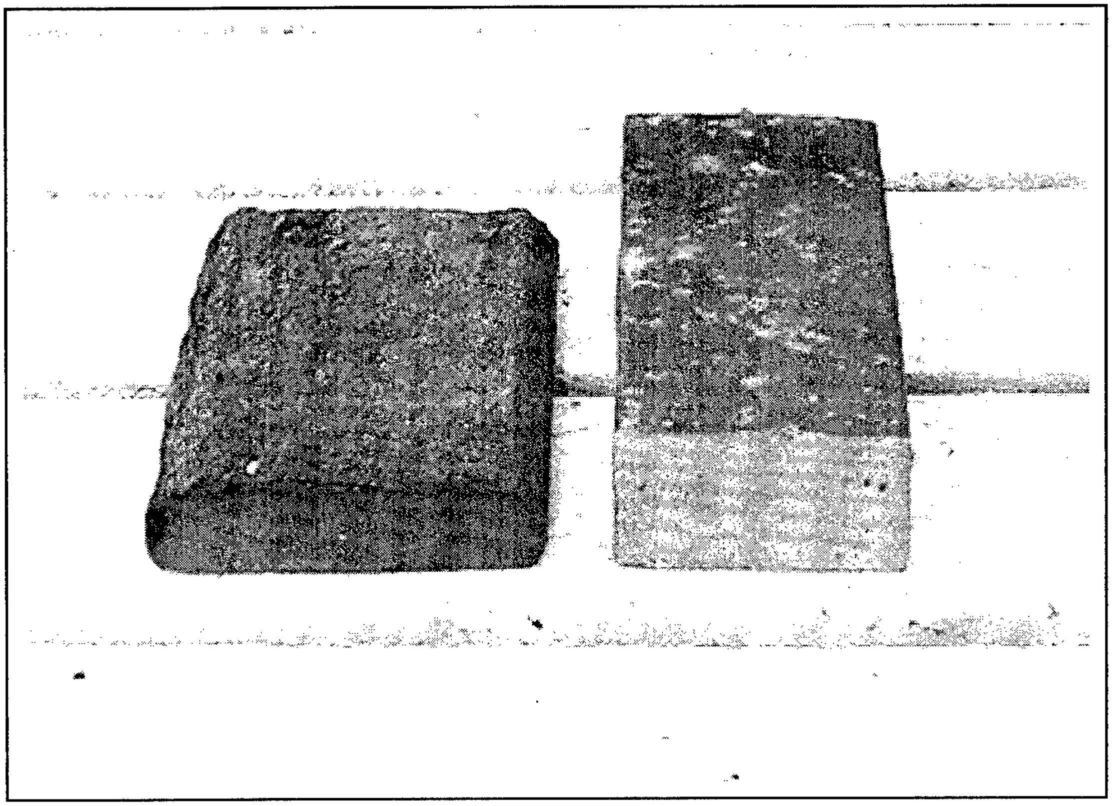

Figure 9. Exposed and unexposed samples of boards made from recycled plastics and wood.

3 Laboratory Mechanical Property Testing

The participating manufacturers donated and shipped plastic lumber materials for mechanical property evaluations and possible demonstration projects. Each manufacturer product was assigned a letter code, which was used for all mechanical property reporting. This chapter describes the mechanical property testing performed on the submitted products.

Macroscopic Observations

A cross-sectional profile of a piece of plastic lumber, consisting of 100 percent NJCT, is shown in Figure 10. The piece is solid around the perimeter of the cross section while the area around the center (core) contains numerous pores of varying size. These voids are believed to be caused by a combination of factors. Wherever the polyethylene phase crystallizes there will be significant shrinkage. Because of the bulky nature of the profiles, and because polymers do not conduct heat well, the periphery of the extruded product solidifies first, shrinking and pulling away from the mold. The remaining core of molten material will in turn cool slowly, crystallize, and shrink. However, because the outer skin has already solidified, the external dimensions of the piece will stay approximately the same. Consequently, internal pores or voids form. Voids are also thought to be caused by water vapor and other gases that were not vented during processing. A comparison of the density of the outer region with the overall density of a profile gives an estimate of the volume fraction due to voids equal to 10 percent.

A second macroscopic observation is that all cross-sections exhibit cylindrical symmetry. The second phase inclusions are elliptical in nature, with the long axes of the inclusions oriented roughly along circular arcs centered about the centroid of the cross section.

Mechanical Testing Procedures

Testing Problems and Issues

The plastic lumber industry has had no standardized test methods to refer to. Available ASTM testing procedures for plastics are inadequate: they do not address the plastic lumber profile's special composition and structure. A typical profile has many inclusions and voids in its cross-section. ASTM injection-molded "dog bone" samples do not yield properties that are valid for a lumber profile. Also, the uneven nature of the lumber's skin makes obtaining an accurate cross-sectional area problematic. Present ASTM procedures for compressive modulus can be modified for the large profiles, but ASTM standards specifically designed for the lumber profiles are needed for clarity and comparison of stock manufactured by different companies. Standardization will allow the recycled plastic lumber to be graded to several levels of performance, including structural and load-bearing applications. Plastic lumber standards will promote confidence in the end user.

The first step toward defining new standards is the development of sensitive test methods that can obtain reproducible mechanical property data along the lumber profile. The test methods must take into account the typical composition and non-homogeneity of plastic lumber.

Materials and Processing

Ten plastic lumber samples were obtained from eight of the participating manufacturers. (Two companies submitted two grades of product.) The composition of the products varied greatly: some were mixed plastics, some were pure resins, and others contained fillers such as wood pulp or fiberglass. These variations in composition result in wide variations of mechanical properties, and highlight the need for national standards.

Nine of the profiles were 8 ft long and one was 4 ft. All were approximately 3.5 in. square. The profiles are not exactly 3.5 in. x 3.5 in., however, due to non-uniform shrinkage from the mold. This non-uniform shrinkage can be attributed to variations in density or in material along the profile length during extrusion. The profiles were either batch-molded or continuously extruded. The extrusion process for each group of lumber profiles was not provided, but testing the mechanical properties for consistency along the length of the profile will give insight to what method of extrusion was used. Also, observations have shown that some of the continuously extruded profiles were foamed.

Sample Preparation

One profile from each group was cut into approximately 1 ft length samples, in accordance with the slenderness ratio of approximately 11:1 from ASTM D-695-85 for compressive testing of rigid plastics (ASTM 1985). The samples were labeled using an alphanumeric system as follows. The first number represents the profile's number, which was assigned to each lumber piece within a batch sent from that manufacturer. The first letter represents the manufacturer (an arbitrary assignment made on the chronological basis of shipment date), and the next letter represents the position of the test piece along the profile. The profiles were labeled "A" through "H," with the "A" end consistently being the end with the protrusion or nipple (when present) associated with the filling end of the mold. This consistency is necessary to determine what type of extrusion was used, as the mechanical properties will be viewed with respect to their position along the profile. Some samples also were assigned one or two letters in parentheses at the end of the designation to designate color (e.g., "g" is gray) for lumber produced in more than one color.

The samples were cut from the lengths flat and parallel to minimize the toe region on the force-displacement curve. These profiles were cut parallel to within 0.030 in. (less than 0.25 percent of the length and less than 1 percent of the smaller cross-sectional dimension). Cutting with such a high degree of parallelism requires two flat sides. Many of the 8 ft profiles were bowed, however, limiting the ability to create sample surfaces that were perfectly parallel.

To calculate the mechanical properties, a value for the cross-sectional area of each sample is required. Simply using the linear dimensions to calculate area is inadequate due to the surface irregularities noted above. Instead, an effective cross-sectional area was obtained through a specific gravity measurement.

ASTM D792-66 outlines a method of obtaining the specific gravity and density of plastics by water displacement (ASTM 1966). Following method A-3 (for solid plastic samples greater than 50 grams), the samples are weighed in the air and weighed while immersed in water. To keep water from entering the voids present in the cross-section of the material, the ends are sealed with thin plastic tape. The plastic pieces must also be weighted to avoid floating; the immersed weight is required due to the sample's buoyant force. The weights then are related to obtain the specific gravity and the density of the sample. With the density, length, and weight in the air of each sample known to a reasonably high degree of accuracy, the effective cross-sectional area can be calculated.

Mechanical Testing

All mechanical tests were performed on an MTS Model 810 universal tester. Compressive measurements were performed on the 1-ft-long samples. Tensile measurements cannot be performed on small ASTM type samples of this material in a way that would accurately reflect the profile properties. The voids and inclusions in the large molded samples give the profile very different mechanical properties than those found after injection molding the same material. The actuator rate chosen for compressive measurements was 0.254 cm/minute (0.1 in./minute).

Results

The modulus, ultimate strength (at 10 percent strain) and yield strength (2 percent offset) were calculated from the force-displacement data. The specific modulus and specific strength are the modulus divided by specific gravity and the ultimate strength divided by specific gravity, respectively. These "specific" properties display the mechanical properties of the materials normalized with respect to density. This normalization should minimize the effects of voids when comparing the material properties and the effects from different methods of extrusion. Batch extrusion, continuous extrusion, and foaming produce variations in densities, even along the profiles.

The data are grouped in two ways: the average mechanical properties from each of the 10 groups are compared, and the mechanical properties along the profile are compared for each individual sample.

Table 5 contains the averages for the specific gravity and the five mechanical properties from each company, and Figures 11 and 12 represent these data as bar graphs. Clearly, properties differ from company to company. Even samples from the same company, such as 2D(BR) and 2D(G), have variations of more than 20 percent in their mechanical properties. In other words, these are different materials in terms of their mechanical properties and therefore will perform differently from one another in most applications.

The moduli range from 399 MPa to 1320 MPa among the samples. This 230 percent variation in modulis proves that these materials cannot be considered identical, and that they cannot be assumed to perform similarly in many applications. A large range was discovered for ultimate strength—from 8.45 MPa to 21.5 MPa—which results in a variation of 154 percent. Again, this variation is large enough to warrant standards and standardized test methods to ensure that the materials are applied properly. The wide range of materials properties, which is now a liability

to manufacturers, could be a strength when testing and grading methods are established.

Since different methods of extrusion are used among plastic lumber manufacturers, the wide property variations noted above could arise from differences in density that accompany different extrusion processes. The data for normalized mechanical properties of specific modulus and specific strength do not support this theory, however. The specific modulus ranges from 609 MPa to 1680 MPa, resulting in a 175 percent variation. The specific strength ranges from 15.0 MPa to 24.4 MPa, or a 62 percent variation. These are both substantial variations, and prove that density is not the only material parameter responsible for the large variation in mechanical properties from company to company. Feedstocks are also quite different among these products.

Figures 13 through 17 show the specific gravity and mechanical properties for individual samples versus sample position along the profile. These properties may provide a key to determining which type of extrusion process a manufacturer uses. Batch extrusion likely results in a change in physical and/or mechanical properties at one end of the profile, as seen in Figures 13, 14, and 15 (Renfree 1991, p 50). These graphs are curve-fitted to a second-order regression, always resulting in a parabola. Figure 13, which contains the data for sample 1S, shows the specific gravity remaining constant while the three mechanical properties are closely correlated with a downward curvature. The maximum values for the properties are found in the center pieces of the profile, along with the most constant properties for contiguous sections. The data for sample 1E are shown in Figure 14. This graph shows the specific gravity, modulus, and ultimate strength correlated with a positive curvature. The maximum values of these properties are found at the beginning and end of the profile, while the sections contain the minimum but most constant properties. The yield strength remains relatively constant. Figure 15 illustrates the data for sample 1B. The graph shows the specific gravity and the three mechanical properties correlated with a negative slope and slight downward curvature. The maximum values for the properties are found at the beginning of the profile. These three graphs support previous data collected at CRRC (Renfree 1991, p 51). Specific gravity varies lengthwise measurably, indicating that the measurement techniques employed are sensitive.

For continuously extruded profiles, the data might be expected to remain relatively constant. Figure 16 supports this theory: the specific gravity and the three mechanical properties are all relatively constant along the length of the profile. In Figure 17, however, only the specific gravity remains constant along the length of the profile. While the yield stress and the ultimate strength follow a similar

pattern, the modulus varies randomly over the length of the profile. Since only one profile from group L was tested for this study, more profiles from group L would have to be tested before conclusions could be drawn about the mechanical properties' variation with position.

Figures 13 through 17 may also be used to help determine which sections of profile samples should be cut for future tests. Flex tests, creep tests, three-point bending tests and more compression experiments are necessary to determine standardized test methods. These future experiments should be performed on contiguous sections of a profile which have the least variation in physical and mechanical properties. For example, the central section of a batch-extruded profile should be investigated because mechanical properties change at the ends. For more compression tests that require samples of 1 ft, the samples should always be taken out of the section of the profile that has consistent mechanical properties (e.g., the central section of batch-extruded materials.

Discussion of Results

The strength and stiffness of commercially produced samples fall far short of the best materials produced in earlier studies (Ehrig 1992). The main shortcoming of these materials, as compared to structural softwoods, is in the much lower modulus. Most of the commercial products provided fell at or below 10 percent of the modulus of pine (Lynch 1974). The data show the extent of variation in physical and mechanical properties for different manufacturers of recycled plastic lumber. The need for standards and standardized test methods is readily apparent. Future research will be necessary to determine and validate such standards.

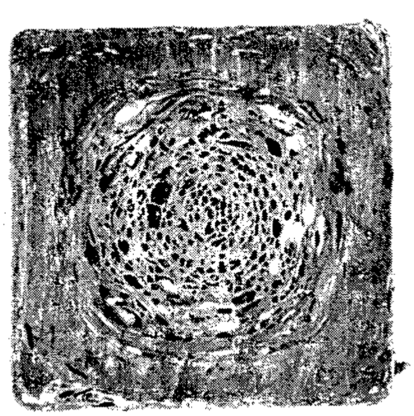

Figure 10. Cross-sectional profile of a plastic lumber made from 100 percent curbside tailings.

Table 5. Average values of specific gravity, modulus, specific modulus, yield stress, ultimate strength, and specific strength for each sample type.

Sample	Specific Gravity	Modulus (MPa)	Specific Modulus (MPa)	Yield Stress (MPa)	Ultimate Strength	Specific Strength (MPa*cm^3/g)
51A	0.2789	262	840	4.89	5.41	19.4
1B	0.7012	427	609	9.52	13.0	18.6
2D(br)	0.8630	588	682	11.5	16.0	18.5
2D(g)	0.8098	800	988	14.5	19.7	24.3
1E	0.8620	557	647	12.2	16.7	19.4
1F	0.7888	746	945	15.1	19.4	24.6
1J(b)	0.7534	643	854	13.1	16.3	21.6
1J(w)	0.9087	759	836	14.9	19.5	21.4
23L	0.7856	1320	1680	11.8	13.3	16.9
1M	0.5652	399	705	6.65	8.45	15.0
1S	0.9090	555	610	11.5	14.1	15.5
1T	0.8804	813	921	15.5	21.5	24.4
9U	0.774	598	769	12.6	16.6	21.3

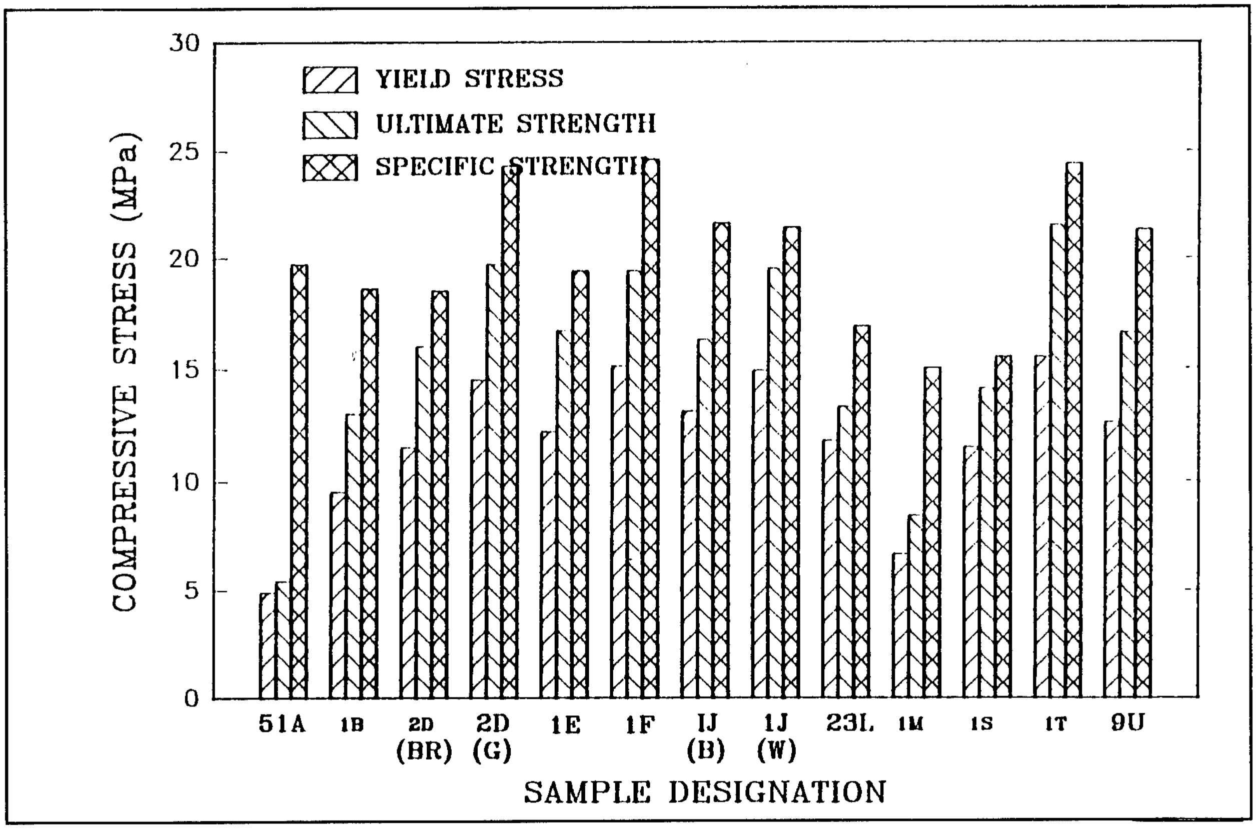

Figure 11. Average values of yield stress, ultimate strength, and specific strength of each sample type.

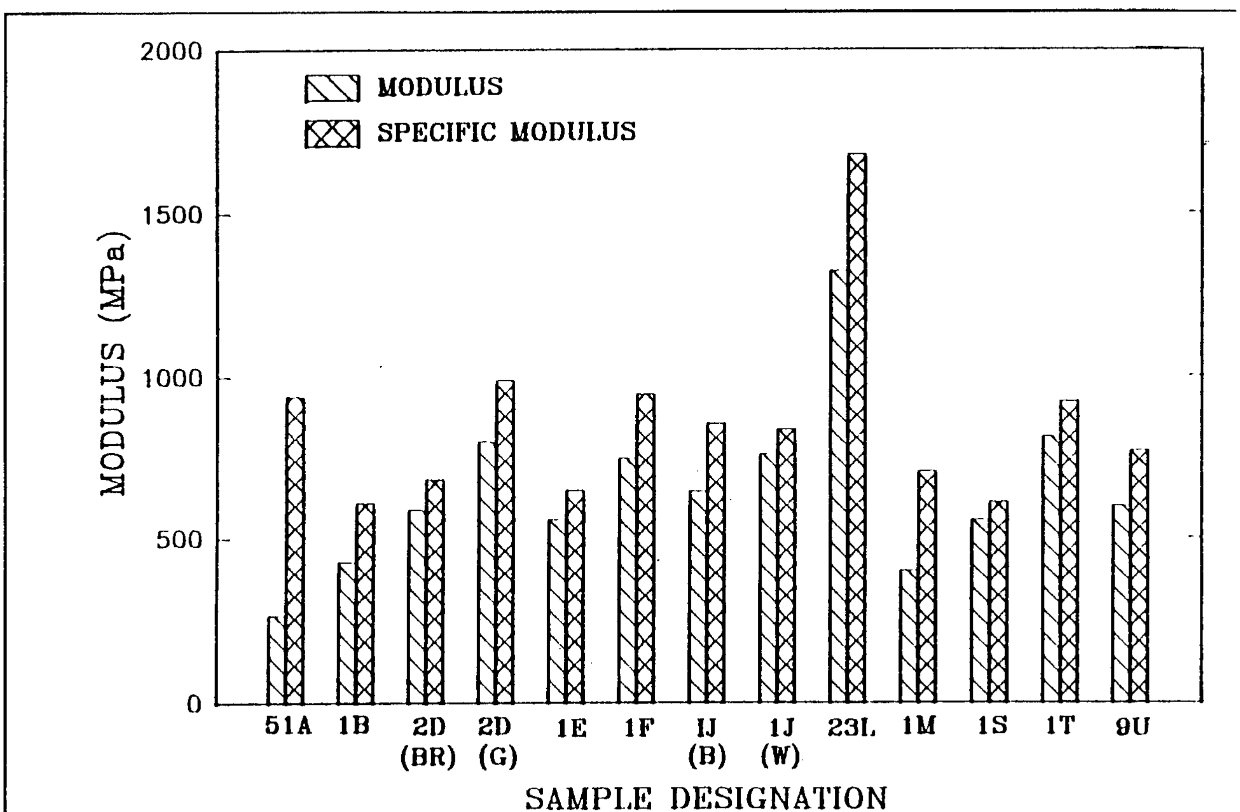

Figure 12. Average values of modulus and specific modulus for each sample type.

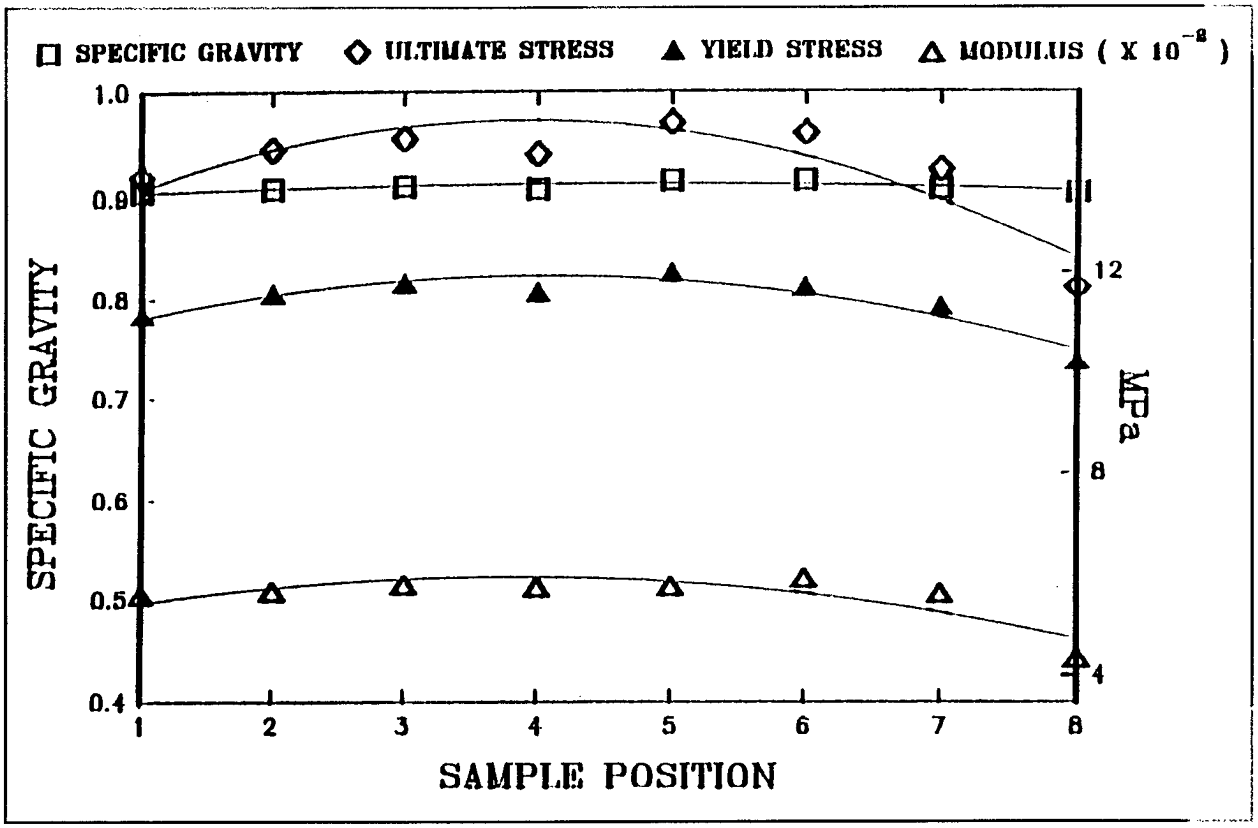

Figure 13. Mechanical and physical properties of Sample 1S vs. position.

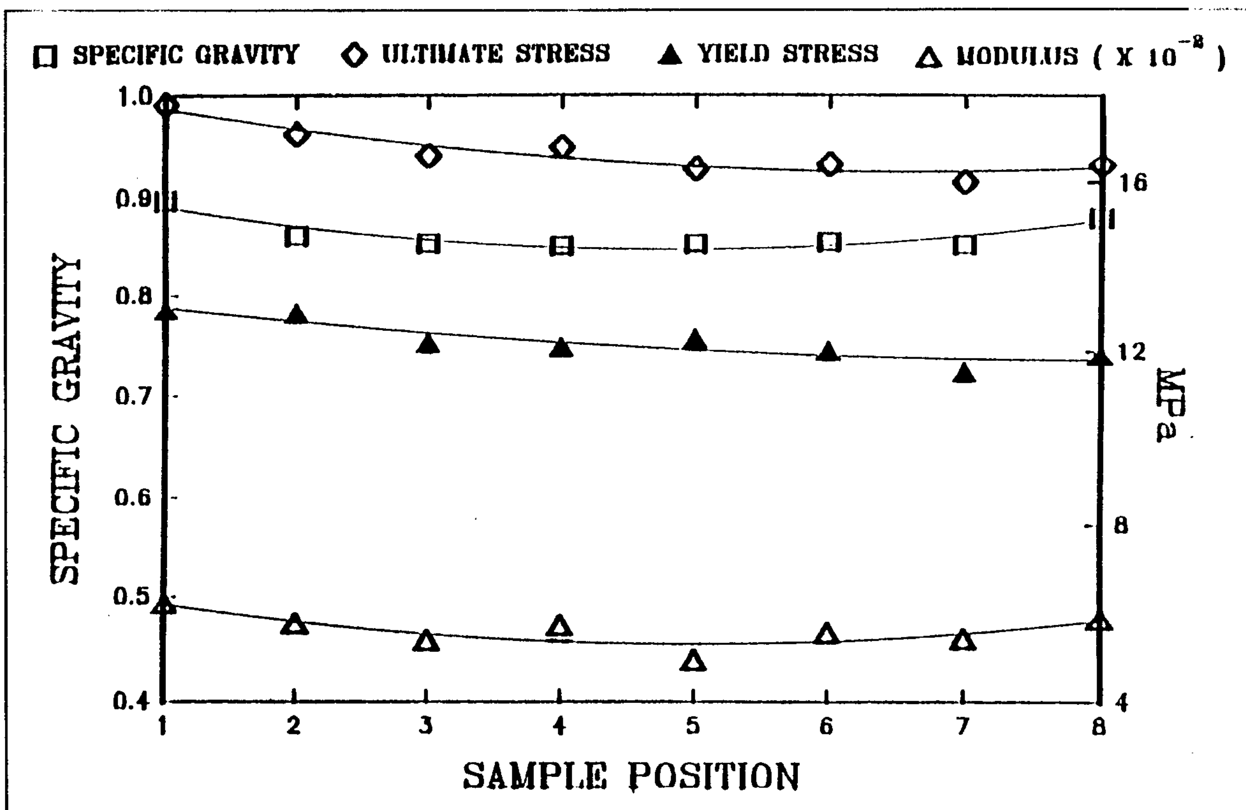

Figure 14. Mechanical and physical properties of Sample 1E vs. position.

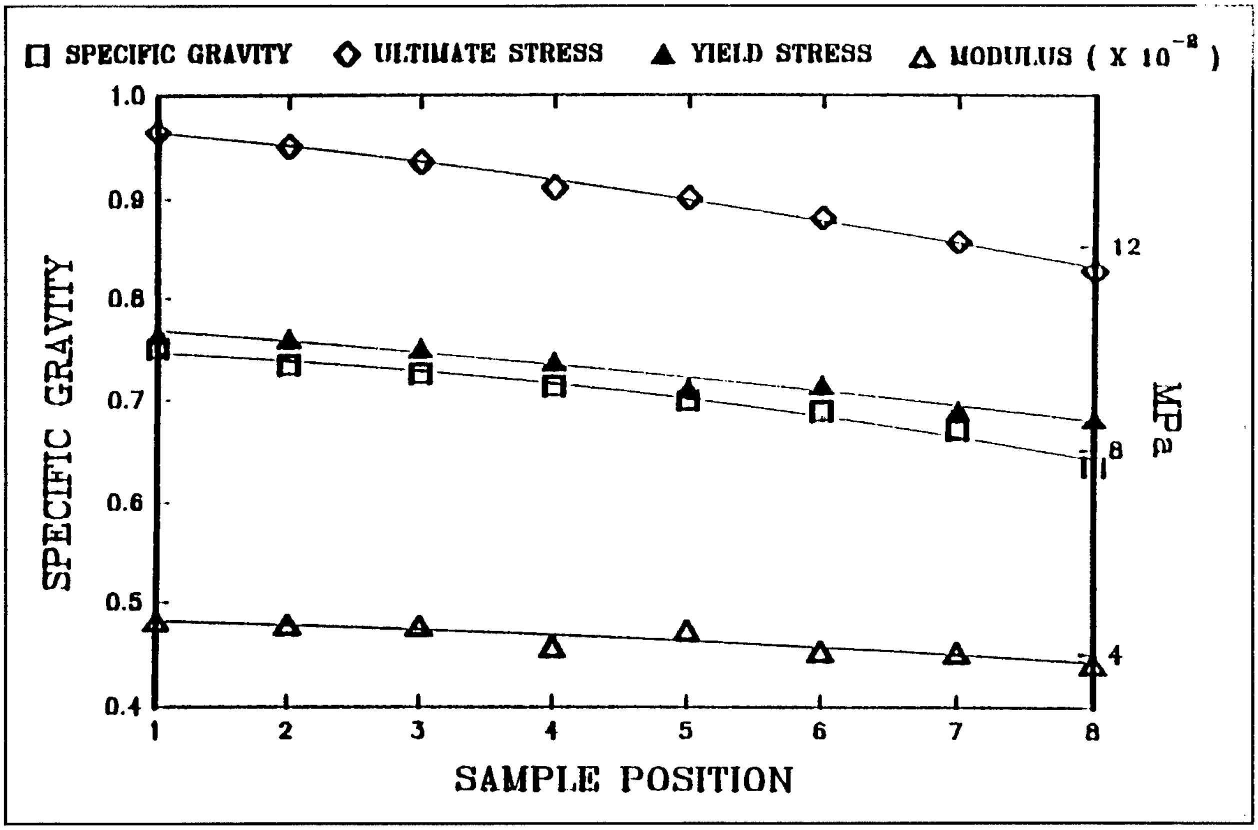

Figure 15. Mechanical and physical properties of Sample 1B vs. position.

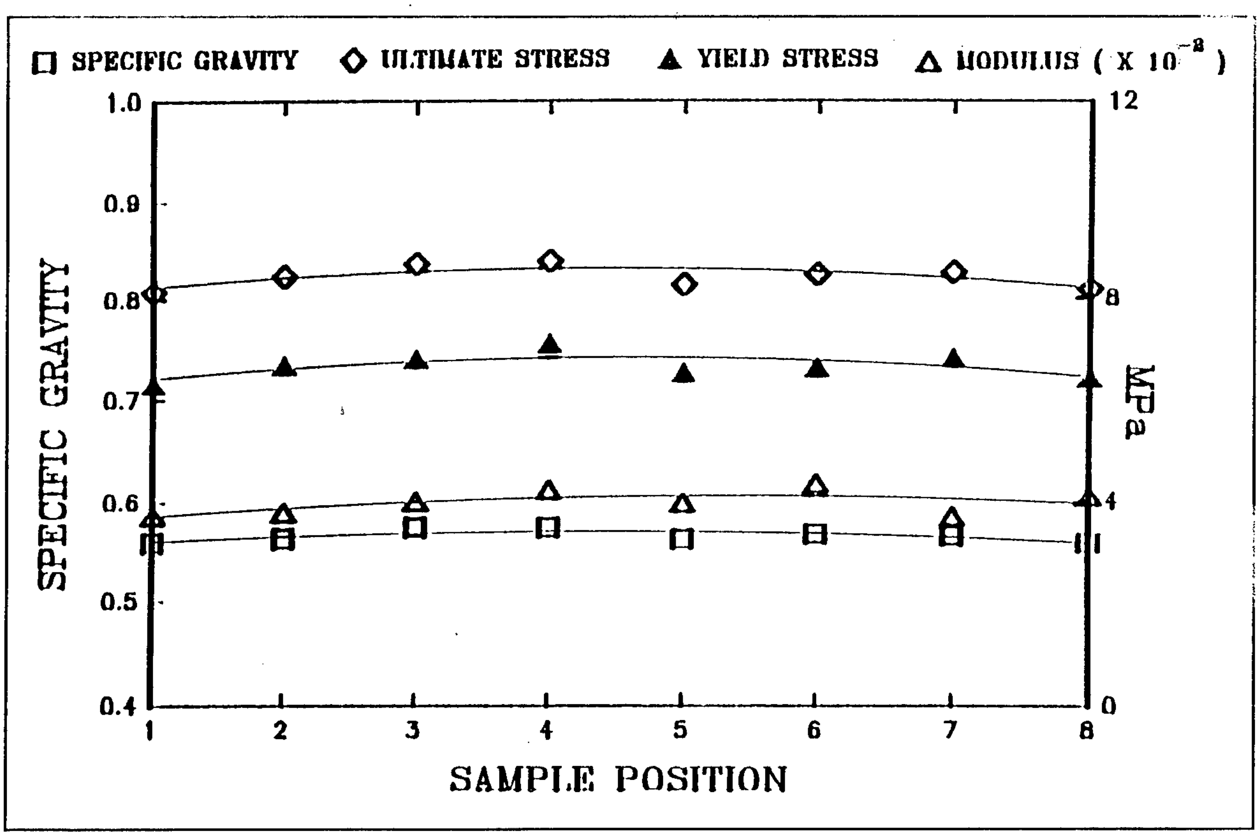

Figure 16. Mechanical and physical properties of Sample 1M vs. position.

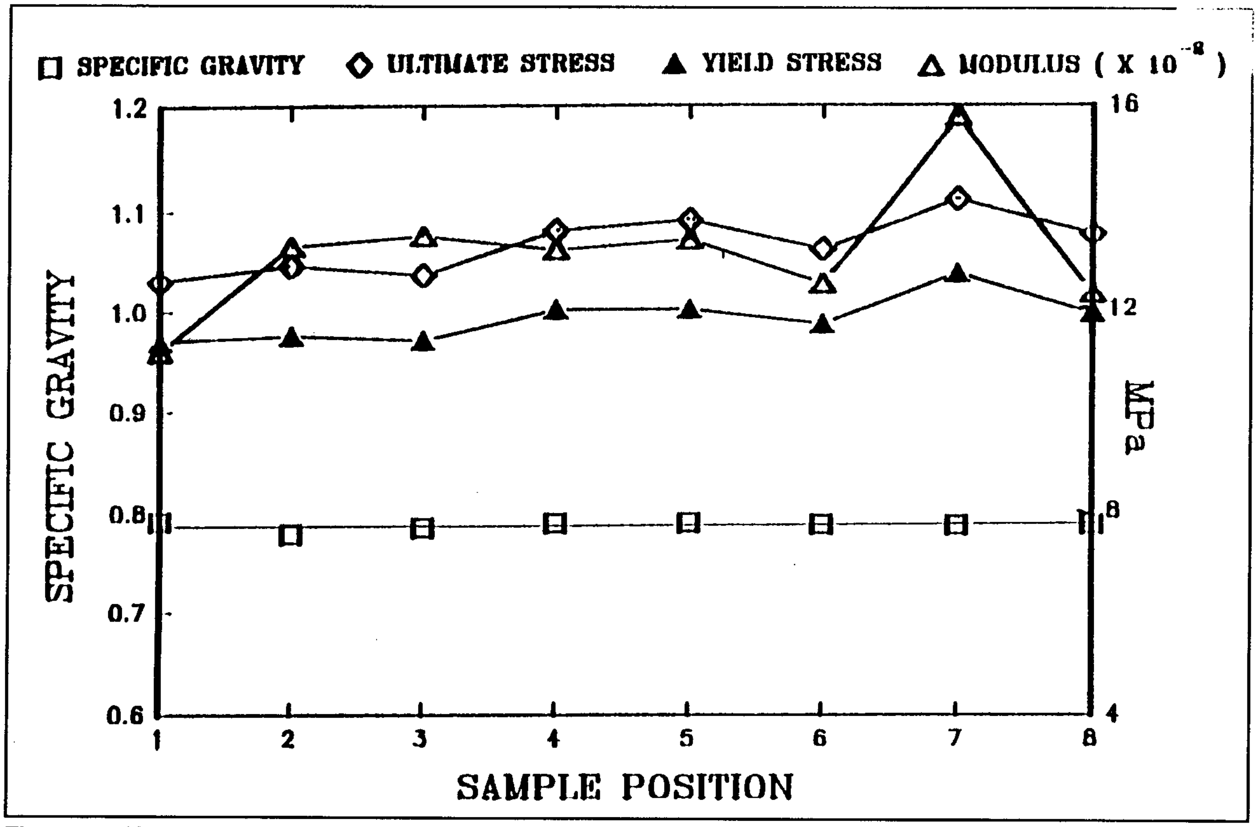

Figure 17. Mechanical and physical properties of Sample 23L vs. position.

4 Predictive Methods

Introduction

In addition to understanding the mechanical properties of as-manufactured plastic lumber, it is very important to have methods available for predicting any changes in material properties over time. A thorough understanding of property time-dependence is necessary so designers and engineers can reliably predict the long-term behavior of plastic lumber in load-bearing applications.

Work has been done on many aspects of recycled plastic lumber, including characterization (Hill et al. 1994), morphology (Van Ness et al. 1994), fatigue (Yang, Bennett, and Beatty 1994), wear/abrasion (El-Rahman et al. 1994), and fractography (Chen et al. 1994). A great amount of work also has been performed regarding the mechanical properties, much of it centered on developing effective test methods for accurate, reproducible mechanical property data. This is important because HDPE, the major component of most recycled plastic lumber, has been shown to have modulus and compressive strength values that are only 9 percent and 42 percent of the respective values for the hardwood white oak (U.S. Department of Agriculture 1987; Modern Plastics 1991) (parallel to grain). Further reductions in these values over time would have great implications for various load-bearing applications.

Previous work on rate-dependence and properties has involved virgin homogeneous polymeric materials in tension. The mathematical model based on the Williams-Watts equation generates stress-strain curves at different temperatures and strain rates from two stress-strain curves. These predictions have been shown to be accurate for virgin glassy and crystalline polymers up to 15 percent strain (Matsuoka 1986, p 33-40).

This chapter focuses on determining whether a predictive mathematical model for polymers in tension could be applied with accuracy to recycled (possibly composite) polymeric materials in compression. This work will help establish quick, inexpensive predictive techniques for the long-term mechanical properties of recycled plastic lumber.

The mechanical properties presented here are evaluated at three strain rates to further establish the effectiveness of the testing protocol discussed in Chapter 3, and to verify the degree of material variations among manufacturers. This step also displays the strain rate dependence of the materials and provides the necessary information for performing—and checking the accuracy of—predictive techniques. Two strain rates are needed to predict stress-strain curves at other strain rates, and the third strain rate is used to check the prediction. The fastest and slowest strain rates were chosen to be above and below the intermediate strain rate by a factor of 100. This factor was chosen in order to most effectively display the strain rate dependence and to check predictive techniques over a wide range of strain rates.

Empirical techniques were applied to the data to obtain predictive mechanical property data. The results are compared with the experimental data. Stress-strain curves at different strain rates are produced from a stress-strain curve at a single strain rate. A close fit of predicted and measured stress-strain relationships with this technique would allow the modulus, yield stress, ultimate strength, and energy to failure to be predicted for a material at many different strain rates from just two tests. A degree of accuracy with these techniques would provide knowledge of long-term mechanical properties without the long-term tests normally required.

Experimental Methodology

Testing Procedure

These compressive tests were based on ASTM D 695-91, which was modified for use on recycled plastic lumber samples. As discussed in previous work (Sachan et al. 1994), the ASTM sample size was modified based on a slenderness ratio, allowing for larger compressive testing samples. The ASTM procedure was also modified for testing speed. The ASTM-recommended standard testing speed was 0.13 cm/min. Modification was necessary to obtain the three strain rates required for this study.

For testing at three strain rates, the actuator rates chosen were: 0.00245 cm/min (0.001 in./min), 0.245 cm/min (0.1 in./min), and 24.5 cm/min (10 in./min). These actuator rates resulted in strain rates of 0.0083 percent/min, 0.83 percent/min, and 83 percent/min, respectively. These strain rates differ by two orders of magnitude each, and were chosen to most effectively display the strain rate effects upon the mechanical properties. For each strain rate, five samples were tested from each group.

Experimental Results

The modulus, yield strength (2 percent offset), and ultimate strength (at 10 percent strain) were calculated from the force-displacement data. Compressive tests were performed at three different strain-rates to observe the strain rate dependence of these materials.

Table 6 shows the average values for the three mechanical properties from each group at each of the three different strain rates. Table 7 shows the coefficients of variation for the physical and mechanical properties at each of the three different strain rates. These samples came from the center section of the profile that was found to have the most consistent physical and mechanical properties.

Variations in physical and mechanical properties are seen to exist at every strain rate. Furthermore, there is no recognizable relationship between strain rate and coefficients of variation (i.e., higher strain rate does not necessarily result in higher coefficients of variation). Finally, these variations on a per-company basis are also smaller than those accepted in woods used for structural applications.

Figures 18 through 21 show stress-strain curves for four representative participating manufacturers, B, D(br), F, and L, at the three different strain rates. The curves show vividly what Table 6 described numerically: the modulus, yield stress, and ultimate strength increase as the strain rate increases. The curves regenerate their general shape, but with higher or lower modulus, yield, and ultimate points depending on the increase or decrease of the strain rate. This is expected behavior for polymers undergoing stress-strain tests at different strain rates (Matsuoka 1986, p 25).

The exception to the increases in stress with increase of strain occurs when samples catastrophically fail (e.g., fracture, buckle). In Figure 18, the company B sample failed through fracture at the fastest strain rate, causing the stress to drop.

The data shown in Table 7 were taken only from the 4 ft center sections of the 8 ft profiles. Clearly, mechanical property values vary from company to company. The variation in modulis shows that materials from different manufacturers cannot be considered identical, and they would not perform similarly in many load-bearing applications. The range in strength shows large enough variation to warrant the use of standards and standardized test methods to determine appropriate applications, even though the variation in properties for each company was small for this limited experiment. These data also show that high modulus values do not necessarily coincide with high strength.

As can be seen from Table 6, the large variations exist at slower and faster strain rates also. The variations in mechanical properties of materials from different manufacturers remain valid for tests performed at varied strain rates.

Predictive Techniques

Stress-strain curves are invaluable tools in studying the mechanical behavior of materials. From these experimental curves, the modulus, yield stress, strength, and toughness can be obtained. These curves are different for the same polymer tested at different strain rates and temperatures. An empirical mathematical model has been developed that enables researchers to predict stress-strain curves at different strain rates for polymeric materials (Matsuoka 1986, pp 24-25). This model can be extended to encompass prediction of creep data. The model is useful in predicting both long- and short-term mechanical behavior of a polymeric material. For the recycled plastic lumber industry, the ability to predict the mechanical behavior of a plastic lumber profile at different strain rates is an important step toward establishing standardized test methods and lumber grades.

Stress-Strain Curves

Using the simplest case of viscoelastic behavior—linearly viscoelastic behavior—and the Boltzmann superposition principle, a stress-strain curve can be calculated from an experimentally obtained relaxation modulus. Consider a simplified case of visco-elastic behavior with a single relaxation time, τ

$$E(t) = E_0 \exp(-t/\tau) \quad \textbf{[Eq 1]}$$

where E(t) is the relaxation modulus at time t, and E_0 is the initial elastic modulus (Matsuoka 1986, p 25). Now, consider that the strain could be made to increase at a constant rate, $\dot{\epsilon}$, to produce the equation

$$\sigma(\epsilon) = E_0 \dot{\epsilon} \tau [1 - \exp(-\epsilon/\dot{\epsilon}\tau)] \quad \textbf{[Eq 2]}$$

In this ideal case, stress-strain curves for amorphous polymers can then be calculated from Equation 2. For these curves, when $\dot{\epsilon}$ or τ vary the curve moves along both the x and y axes by the same amounts, resulting in curves with identical shapes (Matsuoka 1985, p 25).

In reality, however, the time dependence of stress relaxation or creep experiments requires representation by a wide distribution of relaxation times. Thus, the single relaxation time model found in Equation 1 must be modified. Equation 1 can be replaced with the Williams-Watts equation, which represents a wider distribution:

$$E(t)=E_0\exp[-(t/\tau)^{\beta}] \qquad \text{[Eq 3]}$$

where $\beta<1$ and is an empirical factor which accounts for a distribution of relaxation times. Since β is temperature-dependent based on the dependence of τ, β and τ may be grouped with time t for convenience in the Williams-Watts equation. The result is n, a unitless parameter, defined as the slope of the log E versus log t plot

$$-n=\frac{dlogE}{dlogt}=-\mathrm{B}(\frac{t}{\tau})^{\mathrm{B}} \qquad \text{[Eq 4]}$$

Now, Equation 2 can be modified to represent a broader range of distribution times by substituting $(\dot{\epsilon}\tau)^n$ for $\dot{\epsilon}\tau$ (Matsuoka 1986, p29)

$$\sigma=E_0(\dot{\epsilon}\tau)^n(1-\exp(\epsilon/\dot{\epsilon}\tau)^n) \qquad \text{[Eq 5]}$$

This equation is used here as the foundation for scaling stress-strain curves for different strain rates (Matsuoka 1986, p 29).

Unfortunately, identical curves cannot be generated from the experimental data taken at different strain rates, temperatures, and relaxation times for crystalline polymers as they are for amorphous polymers. There are, however, other features of crystalline polymers that make scaling stress-strain curves possible.

A qualitative argument supports an empirical scaling of stress-strain curves (Matsuoka 1986, p 41). Both crystalline and amorphous regions of polymers are viscoelastic. The crystalline region provides a rigid skeletal structure that gives longer relaxation times, while the amorphous region supplies a shorter range of time-dependence. Looking at Equation 2, the $\dot{\epsilon}\tau$ term is associated more with the amorphous regions, while the E_0 is associated more with the crystalline regions. Both terms are important because the transfer of strain energy from the amorphous section to the crystalline section occurs in a stress-strain experiment. Thus, the scaling rule for crystalline polymers is based on energy (Matsuoka 1986, p 41).

For crystalline polymers, stresses at a given strain rate of $\dot{\epsilon}$ increase by a power of the new strain rate, $\dot{\epsilon}^n$, while the strains at a given strain rate of $\dot{\epsilon}$ will decrease by a negative power of the new strain rate, $\dot{\epsilon}^{-n}$ (Matsuoka 1986, p 39). Thus, the stress is multiplied by the scaling factor R_1, and the strain is divided by R_1. The scaling factor R_1 is defined as:

$$R_1 = (\dot{\epsilon}/\dot{\epsilon}_0)^n \qquad \textbf{[Eq 6]}$$

Here $\dot{\epsilon}_0$ is the initial strain rate.

Through use of these equations, stress-strain curves at different strain rates may be generated for crystalline polymers.

Experimentally, it has been shown that the ratio of stresses is equal to R_1 (Matsuoka 1992)

$$\frac{\sigma}{\sigma_0} = \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)^n \qquad \textbf{[Eq 7]}$$

Since in the linear region the modulus is equal to the stress divided by a strain, the strain can be fixed at an arbitrary value to determine the corresponding stresses. In this case, the ratio E to E_0 becomes:

$$\frac{E}{E_0} = \frac{\sigma/\epsilon_{arb}}{\sigma_0/\epsilon_{arb}} = \frac{\sigma}{\sigma_0} \qquad \textbf{[Eq 8]}$$

By combining Equations 7 and 8, the following equation is produced:

$$\frac{E}{E_0} = \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)^n \qquad \textbf{[Eq 9]}$$

With Equation 9 and the scaling factor R_1 defined in Equation 6, scaling of stress-strain curves at different strain rates for crystalline polymers is possible.

Application

Using the theory for semicrystalline polymers outlined in the previous section, stress-strain curves at various strain rates may be generated from experimental data performed at a single strain rate. These predictive techniques are applied to

manufacturers B, D(br), F, and L. Also, in this section, for ease of notation, the three different strain rates will be denoted by numeric subscripts. Subscript 1 will denote the slowest strain rate, 0.0083 percent/min; subscript 2 denotes the middle strain rate, 0.83 percent/min; and subscript 3 denotes the fastest strain rate, 83 percent/min. For example, E_1 represents the modulus at the strain rate of 0.0083 percent/min.

The scaling factor, R_1, is the necessary tool to allow generation of stress-strain curves. To scale curves, the stress is multiplied by R_1 and the strain is divided by R_1. Recall

$$R_1=\left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)^n \qquad \text{[Eq 10]}$$

Therefore, the first step in scaling stress-strain curves is to determine the value of n for each particular manufacturer.

With the modulus values from compressive tests performed at three different strain rates, n can be determined for each company by using Equation 9:

$$\frac{E}{E_0}=\left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)^n$$

For this purpose the following equations were solved for n:

$$\frac{E_1}{E_2}=\left(\frac{\dot{\epsilon}_1}{\dot{\epsilon}_2}\right)^n \qquad \text{[Eq 11]}$$

$$\frac{E_1}{E_3}=\left(\frac{\dot{\epsilon}_1}{\dot{\epsilon}_3}\right)^n \qquad \text{[Eq 12]}$$

$$\frac{E_2}{E_3}=\left(\frac{\dot{\epsilon}_2}{\dot{\epsilon}_3}\right)^n \qquad \text{[Eq 13]}$$

Three different n values were determined for each company's product, and they can be averaged together for the value of n that is used for all stress-strain curve scaling. Each company's product will have its own unique value for n.

These average values of n were then used to solve for R_1, as defined above. Three variables affect the determination of each unique R_1: the manufacturer, the strain rate that is being predicted, and the strain rate that is being used as the initial value. For example, if the stress-strain curve prediction at 0.0083 percent/min is being based on the experimental curve at 83 percent/min, R_1 will have a different value than the R_1 for the same strain rate prediction based on the experimental curve at 0.83 percent/min.

Predictive Results

The average values for n, calculated using the equations presented above, are 0.05027, 0.09807, 0.07322, and 0.03949 for companies B, D(br), F, and L, respectively. (Recall that n is a unitless number.)

Figures 22 through 25 show each company's experimental and predicted data for the strain rate of 0.0083 percent/min. The predicted data were calculated based on the middle strain rate of 0.83 percent/min. For all companies, the predictions yielded the correct modulus values within extremely small error margins (within 3 percent). Once past the yield point, however, the error between curves increased—in some cases up to 50 percent, as seen with company L. Inaccuracies began to show up at between 1 percent to 8 percent strain for the various companies. The error seen in the nonlinear section of the curves ranges from 5 percent for company F to 50 percent for company L. This variation also seems to indicate that the scaling model, which is based on the ratio of the modulus values, will for these materials be most consistently accurate for the linear portion of the stress-strain curve. Once past the yield point, the scaling based on the modulus values is not always able to accurately predict the curve. On a practical level, however, many civil engineers consider a structure to have failed at 3 percent strain (Malcolm McLaren, Jr., personal communication, April 1992). Therefore, for structural materials, this predictive method is accurate up to any relevant factors.

Figures 26 through 29 show each company's experimental and predicted data for the strain rate of 83 percent/min, as calculated from data at 0.83 percent/min. Again, for all companies, the prediction yielded correct modulus values within extremely small error margins (within 3 percent), but once past the yield point, the error increased. The error seen in the nonlinear section of the curves ranges from 5 percent for company D(br) to 20 percent for companies L and F. This variation

further establishes that the scaling model most accurately and most consistently predicts the linear region of a stress-strain curve. Figures 30 and 31 show experimental and predicted data for company B. Figure 30 includes data for the strain rate of 0.0083 percent/min as calculated from 83 percent/min data, and Figure 31 includes data for the strain rate of 83 percent/min as calculated from 0.0083 percent/min data. Both graphs have extremely accurate predicted values over the entire curve. These contrast strongly with the three other companies' predicted data, when calculated from either the slowest to the fastest strain rates or vice versa.

Figures 32 and 33 show experimental and predicted data for company L. Figure 32 includes data for the strain rate of 0.0083 percent/min as calculated from 83 percent/min data, and Figure 33 includes data for the strain rate of 83 percent/min as calculated from 0.0083 percent/min. Both graphs show the inaccuracy of the predicted values as compared to experimental data in the region past the yield point. The data in both figures have errors as great as 45 percent past the yield point. Similar data for companies D(br) and F, not shown in Figure 32 or 33, have errors of 50 percent and 30 percent past the yield point.

Thus, across all the varied strain rate predictions, company B's product receives the most accurate treatment from this model while company L receives the least accurate treatment. The different accuracies for each company further demonstrates the uniqueness of each manufacturer's products.

Examples for every company, however, had provided accurate predictions for the linear region (modulus) of the curve at every strain rate. The respective versions of this model have been employed for both virgin glassy (polycarbonate) and virgin crystalline (HDPE) polymers with accurate results (within 10 percent error) along the entire stress-strain curve (Matsuoka 1986, pp 33-43). However, these materials are composites with a complex morphology, and previous researchers have warned about the difficulty of scaling for morphologically complex materials (Matsuoka 1986, pp 33-43). Furthermore, n may not remain constant for the material immediately after yield. In tensile tests, n returns to an almost identical constant in the steady-state region where necking occurs (Matsuoka 1986, p 32). In compressive tests, this return to a similar, constant n may not occur. Thus, accurate values after yield may be difficult or impossible to obtain consistently for composite materials in compression that are treated with this straightforward model.

Discussion of Results

An empirical, mathematical model was applied to stress-strain data to generate stress-strain curves. The model was established for virgin polymers in tension and

applied here to recycled (sometimes composite) materials in compression. The results are a promising start toward developing effective predictive techniques for recycled plastic lumber. The most critical step in developing a predictive technique is the comparison of experimental and predictive data. The scaling model demonstrated conclusively that it is very accurate for the linear portion of the stress-strain curve, with accuracy diminishing at the greater strains—usually more than 3 percent strain. The inaccuracy at greater strains rise to 50 percent for some companies. Previous work done in tension shows the model to be accurate up to 15 percent strain for HDPE (Matsuoka 1986, p 40). Thus, the model has so far shown itself to be less accurate at strains over 3 percent for recycled, composite materials in compression than for virgin materials in tension.

Prediction of the linear portion of the stress-strain curve, however, may be all that is required for most recycled plastic materials. Many civil engineers consider failure to occur at 3 percent strain. Therefore, predictions accurate to 3 percent strain may be sufficient for structural materials.

Table 6. Average mechanical properties measured at three strain rates.

Strain Rate		0.0083% per min			0.83% per min			83% per min	
Sample	Modulus MPa	Yield Stress MPa	Ultimate Strength MPa	Modulus MPa	Yield Stress MPa	Ultimate Strength MPa	Modulus MPa	Yield Stress MPa	Ultimate Strength MPa
B	317	6.20	9.46	441	9.72	13.2	591	12.9	18.1
D(br)	340	6.92	10.3	571	11.5	16.0	839	18.2	25.3
F	484	9.24	13.6	727	14.7	20.1	950	21.2	28.8
L	1140	7.95	9.04	1320	12.4	13.7	1640	17.4	18.2

Table 7. Coefficient of variation for the mechanical properties measured at three strain rates.

Strain Rate		0.0083% per min			0.83% per min			83% per min	
Sample	Modulus %	Yield Stress %	Ultimate Strength %	Modulus %	Yield Stress %	Ultimate Strength %	Modulus %	Yield Stress %	Ultimate Strength %
B	6.24	2.29	1.69	6.85	4.68	2.94	9.66	7.96	11.58
D(br)	4.04	1.57	2.19	7.99	3.87	4.91	13.8	13.57	6.67
F	11.5	1.99	1.13	9.48	2.80	3.10	5.39	4.16	2.94
L	3.12	8.98	3.87	2.76	10.04	6.25	10.2	8.6	6.90

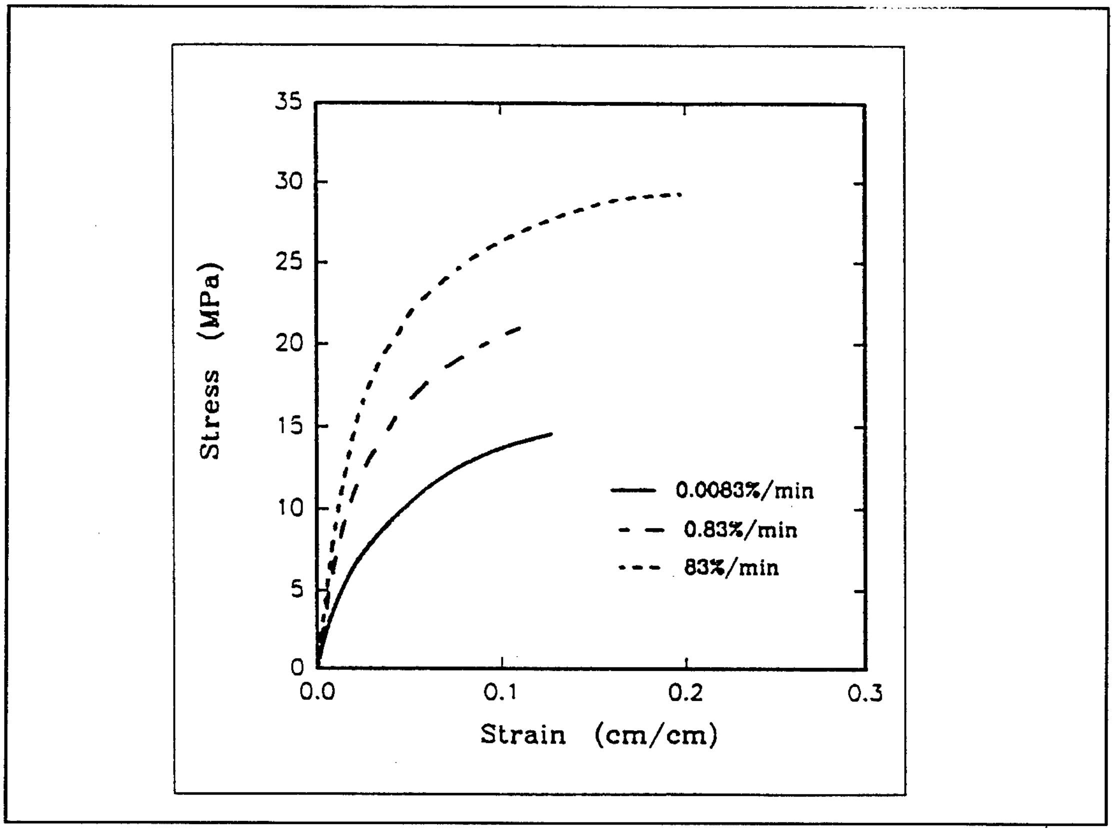

Figure 18. Company B—Stress-strain curves at three different strain rates.

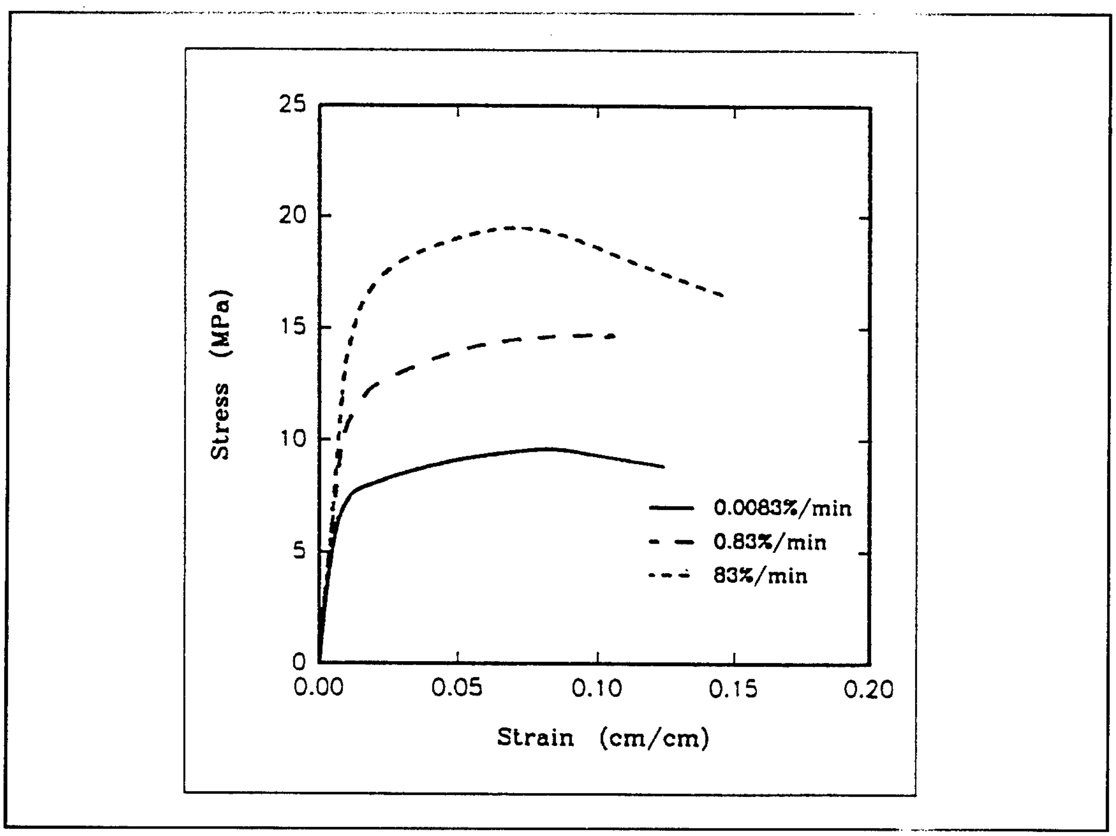

Figure 19. Company D(br)—stress-strain curves at three different strain rates.

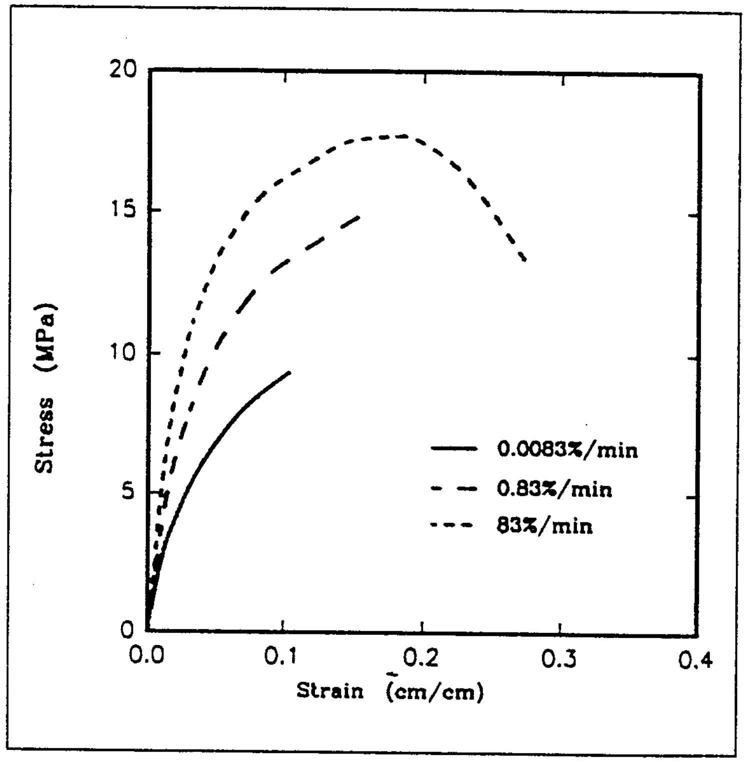

Figure 20. Company F—stress-strain curves at three different strain rates.

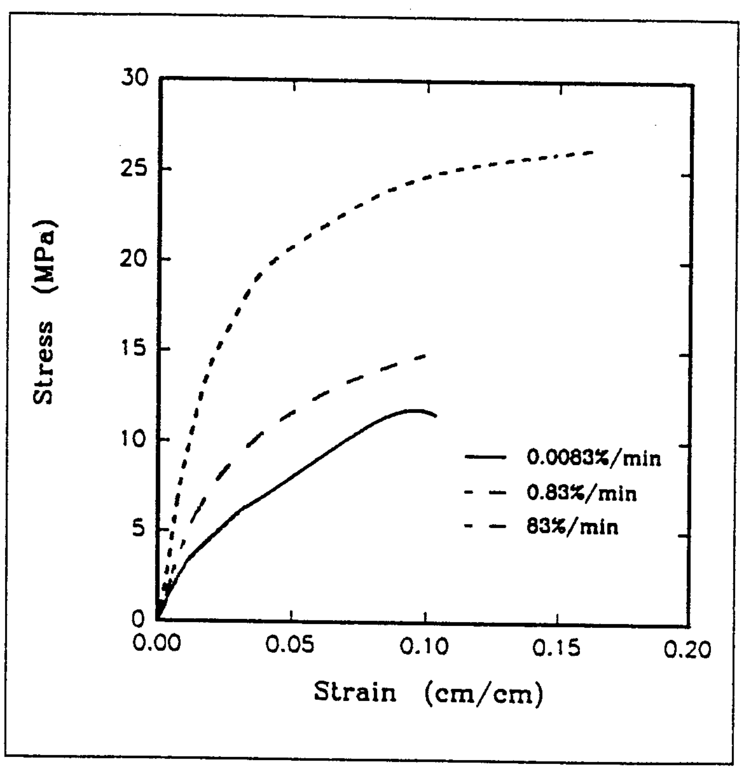

Figure 21. Company L—stress-strain curves at three different strain rates.

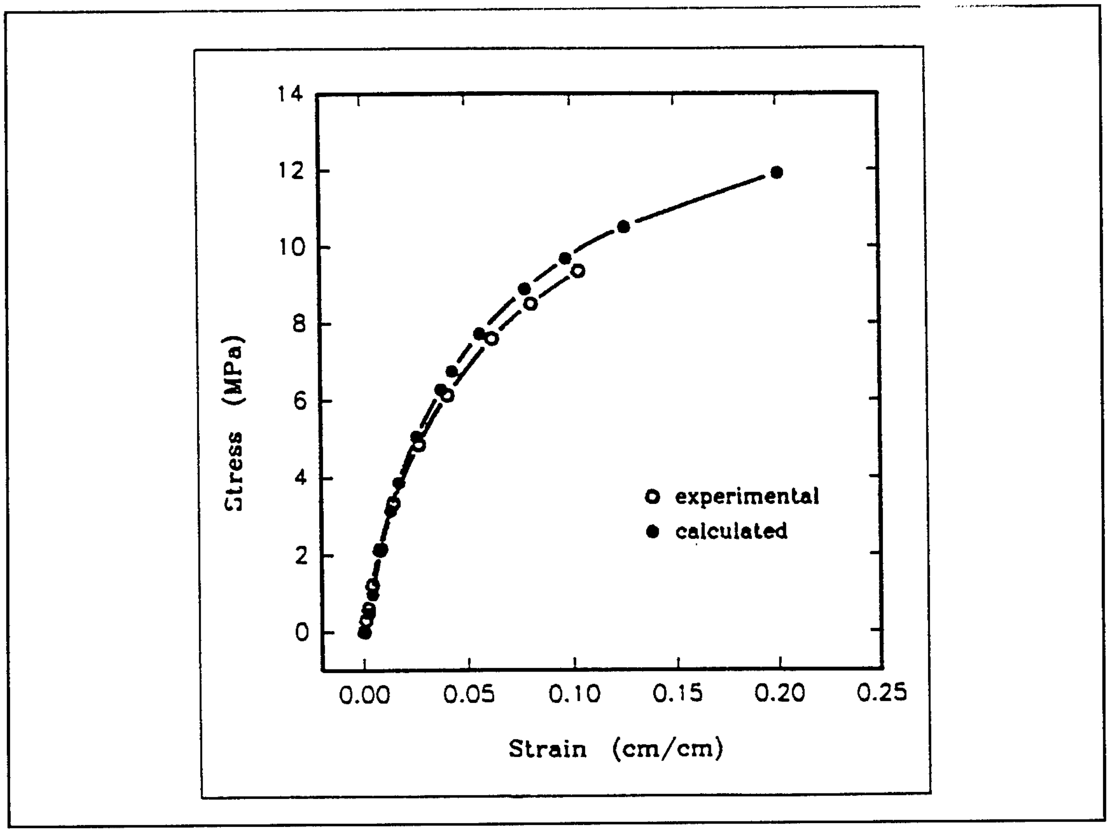

Figure 22. Company B—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 0.0083%/min ($\dot{\epsilon}_0$ = 0.83%/min).

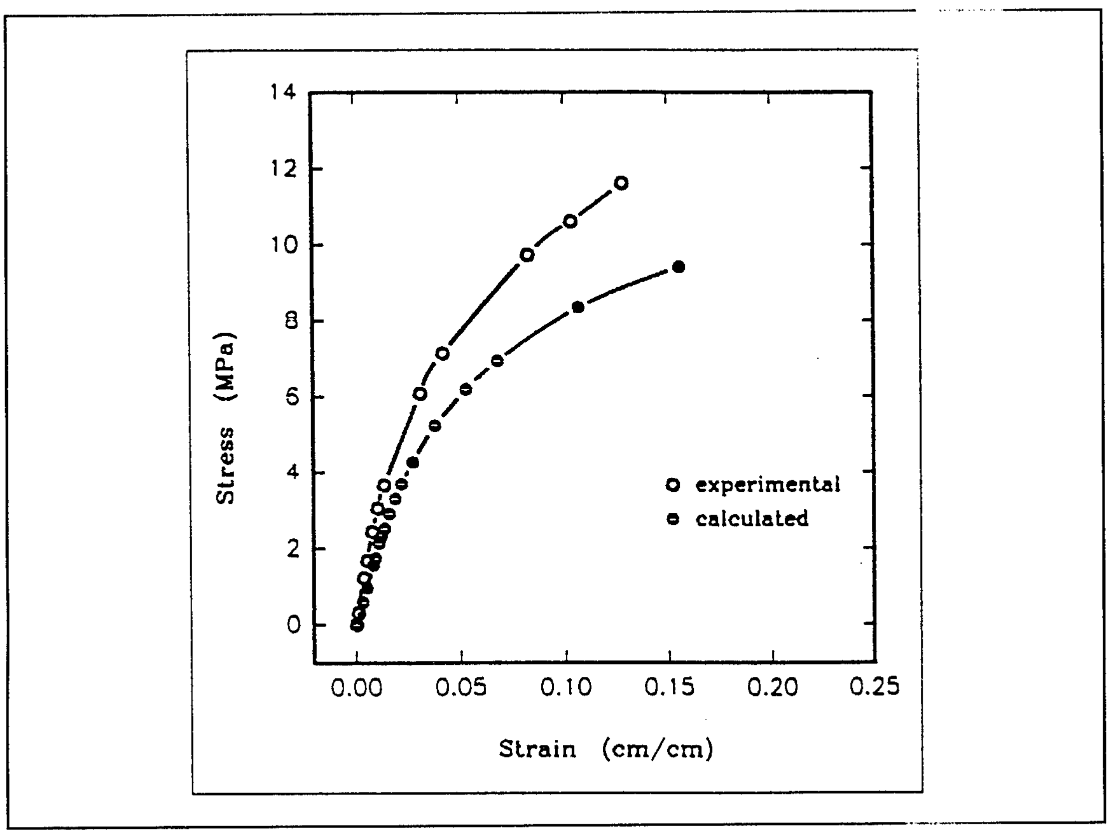

Figure 23. Company D(br)—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 0.0083%/min ($\dot{\epsilon}_0$ = 0.83%/min).

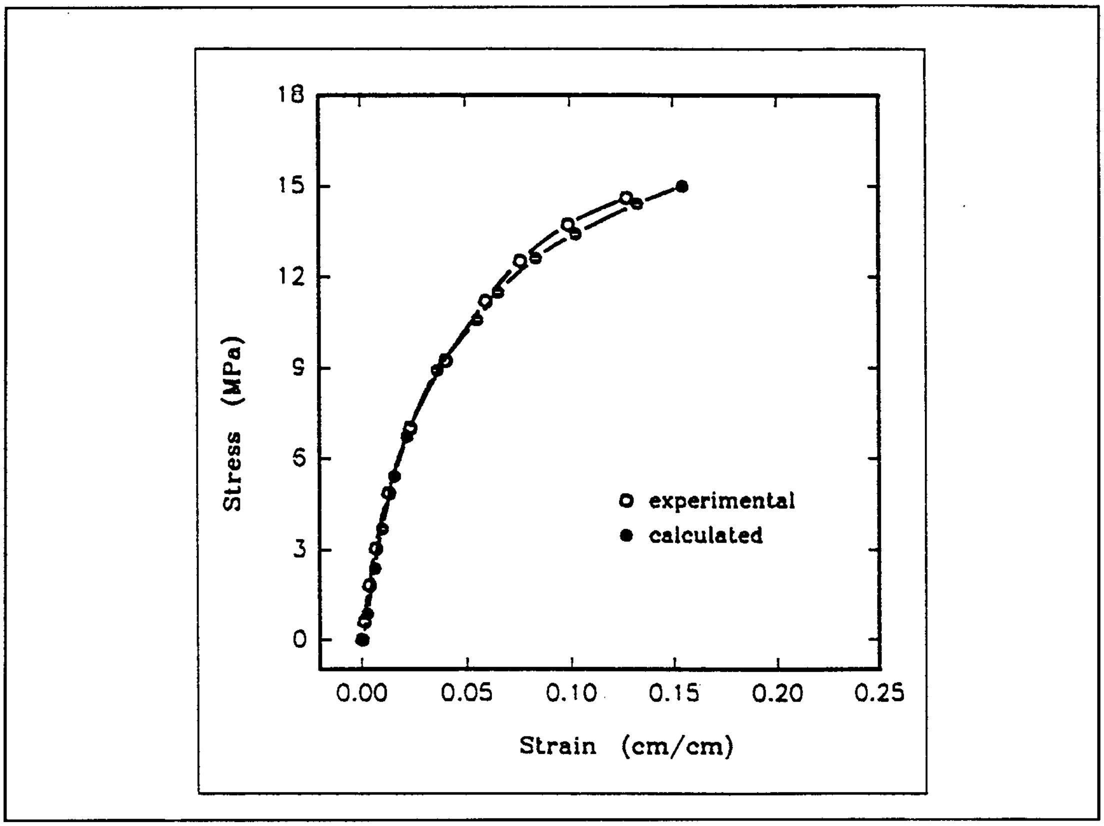

Figure 24. Company F—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 0.0083%/min ($\dot{\epsilon}_0$ = 0.83%/min).

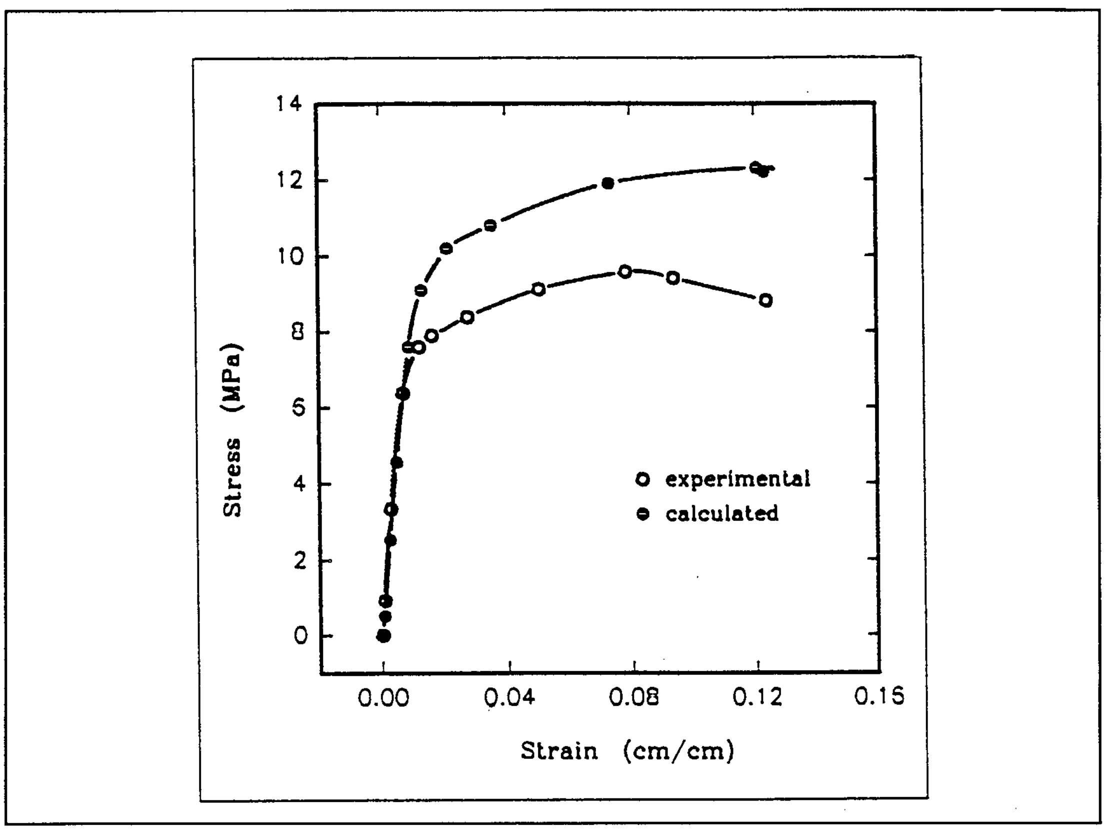

Figure 25. Company L—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 0.0083%/min ($\dot{\epsilon}_0$ = 0.83%/min).

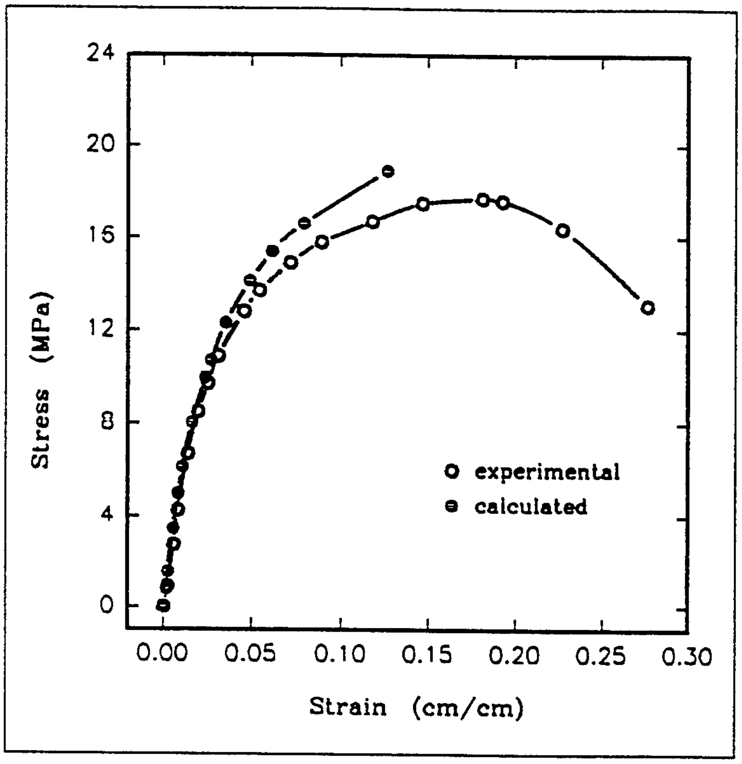

Figure 26. Company B—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 83%/min ($\dot{\epsilon}_0$= 0.83%/min).

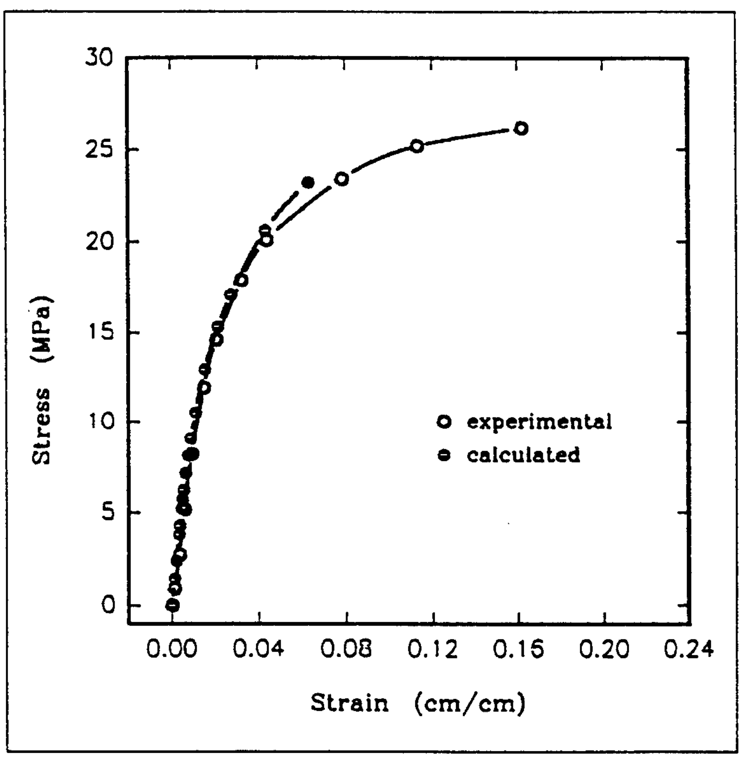

Figure 27. Company D(br)—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 83%/min ($\dot{\epsilon}_0$ = 0.83%/min).

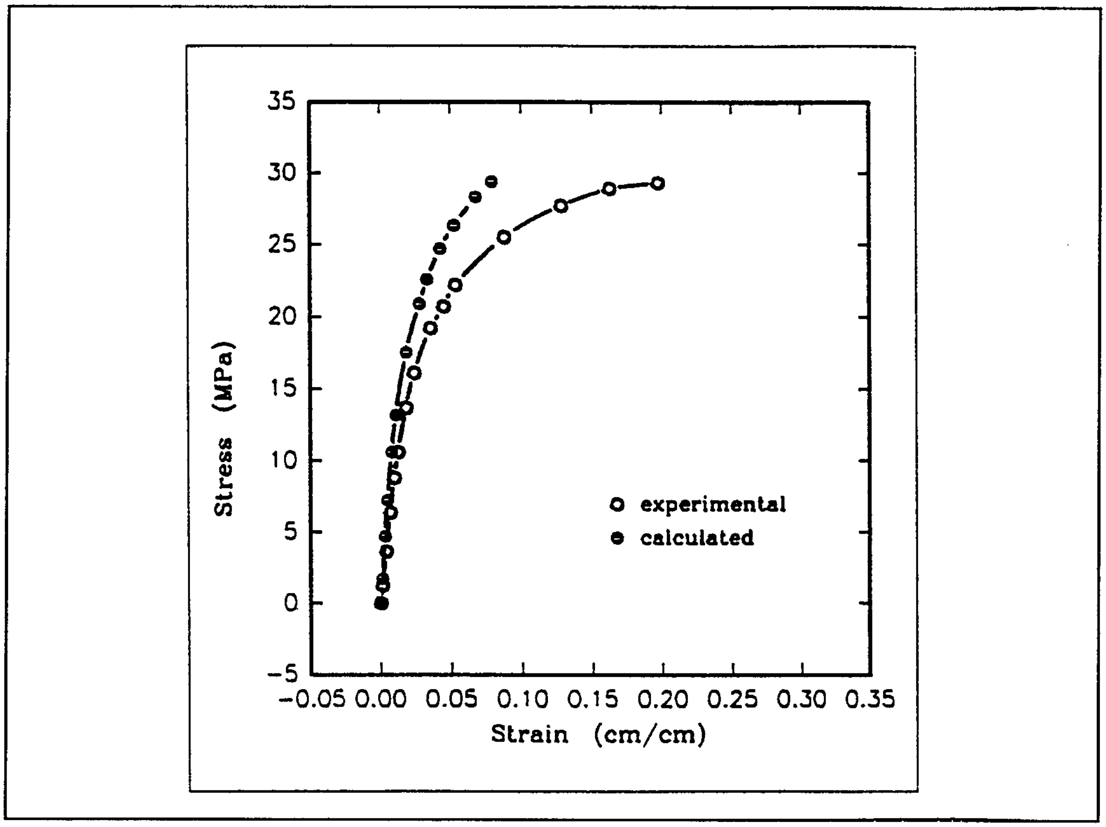

Figure 28. Company F—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 83%/min ($\dot{\epsilon}_0$ = 0.83%/min).

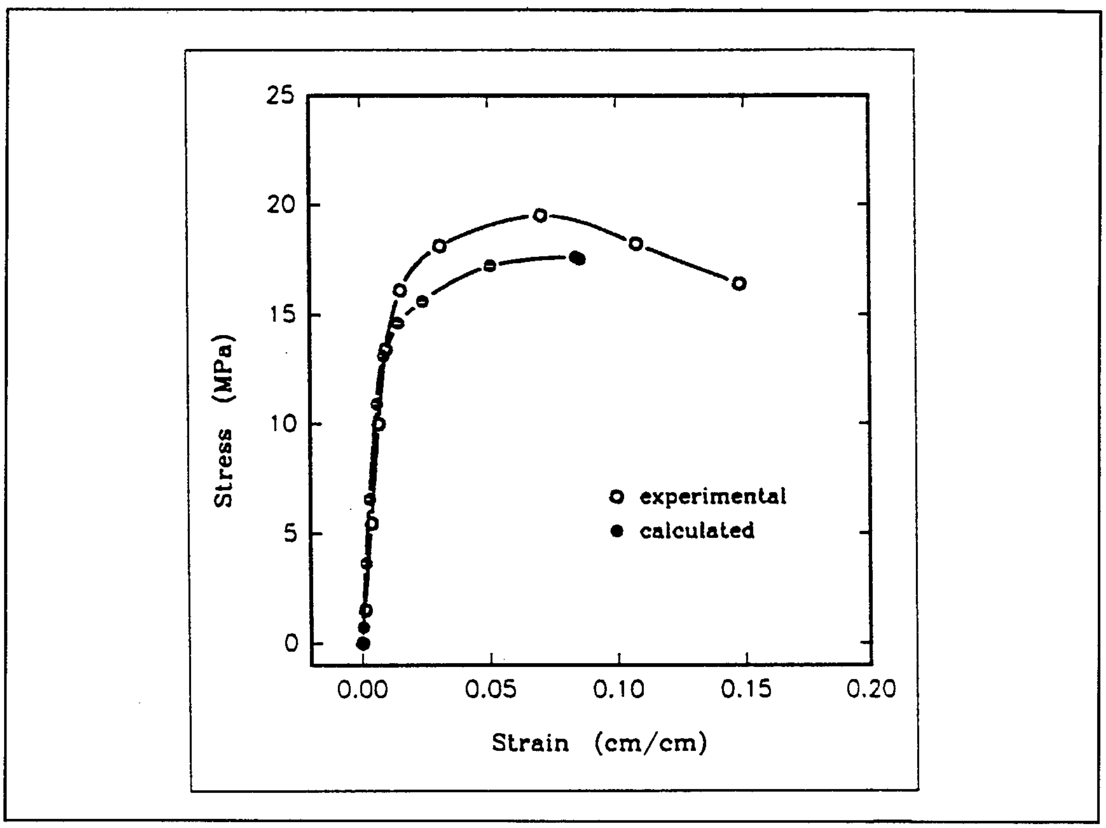

Figure 29. Company L—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 83%/min ($\dot{\epsilon}_0$ = 0.83%/min).

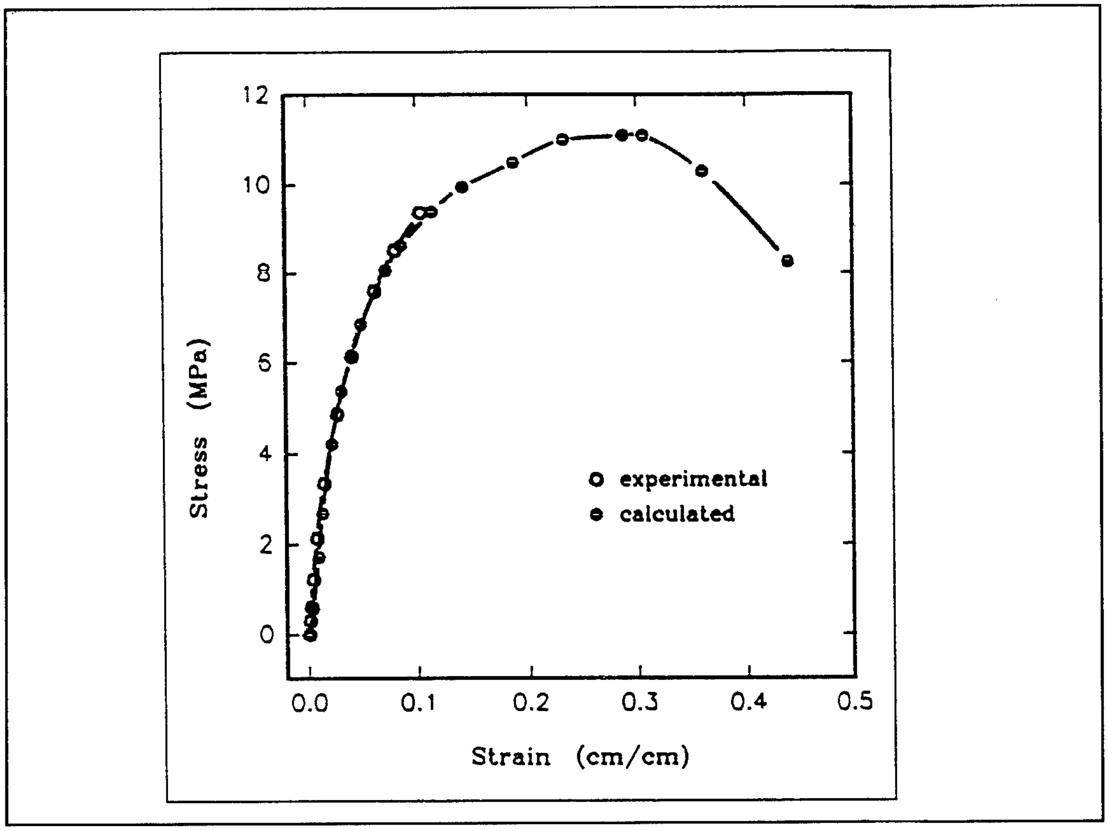

Figure 30. Company B—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 0.0083%/min ($\dot{\epsilon}_0$ = 83%/min).

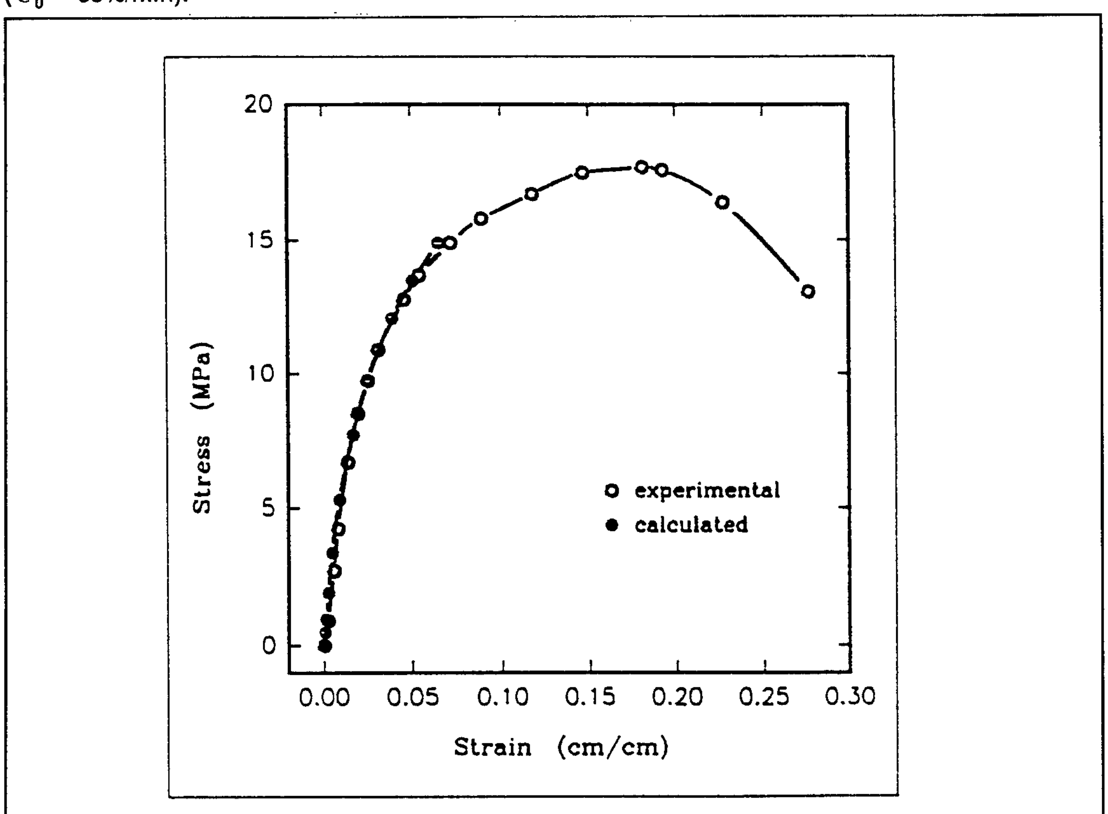

Figure 31. Company B—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 83%/min ($\dot{\epsilon}_0$ = 0.0083%/min).

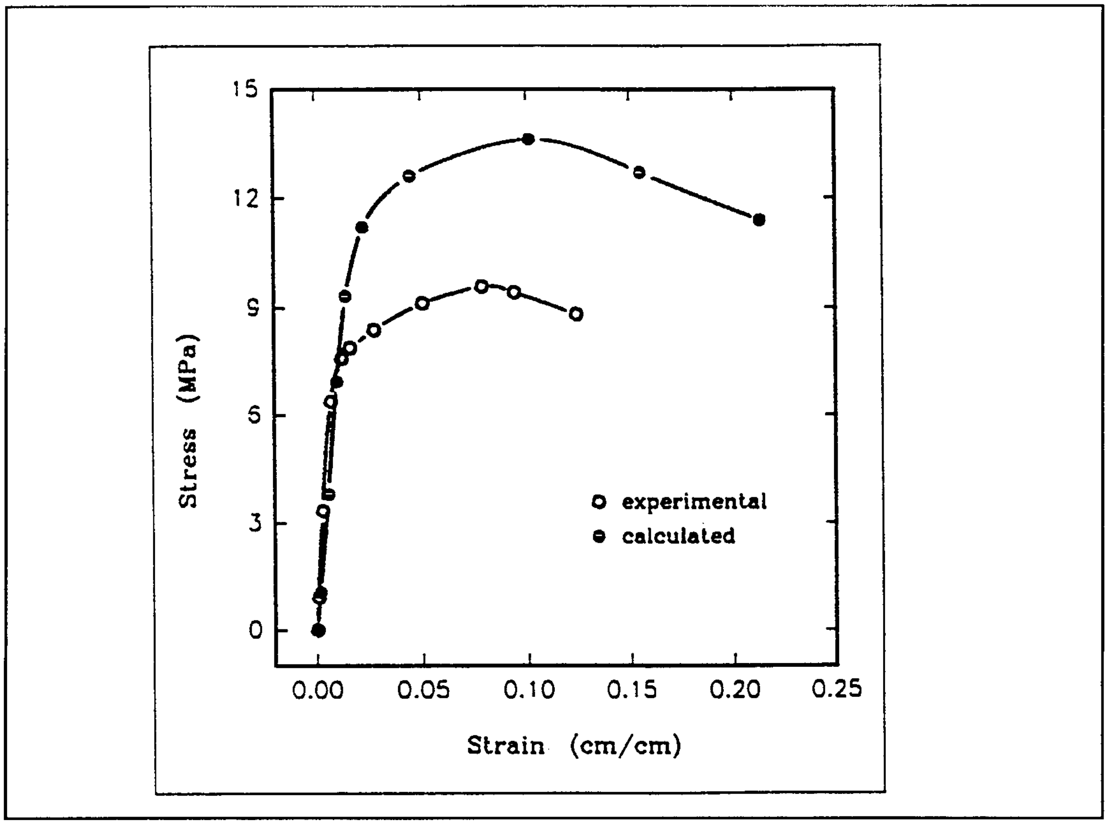

Figure 32. Company L—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 0.0083%/min ($\dot{\epsilon}_0$ = 83%/min).

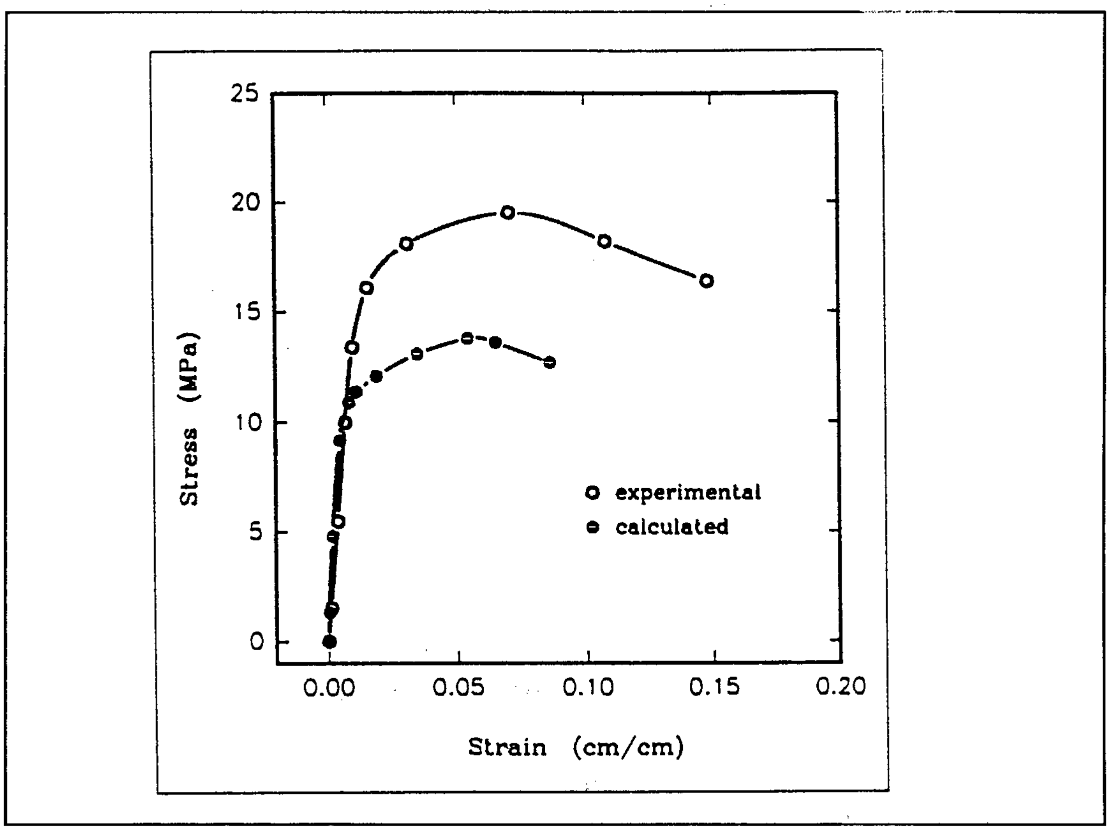

Figure 33. Company L—experimental and predicted stress-strain curves at $\dot{\epsilon}$ = 83%/min ($\dot{\epsilon}_0$ = 0.0083%/min).

5 Design Considerations

Mechanical Properties

Strength

The ultimate strength of plastic lumber is similar to published design value data on softwoods (Ehrig 1992). Douglas fir-larch has design values of 11.7 MPa (1700 psi) for compression and 6.89 MPa (1000 psi) for tension (NFPA 1991). Plastic lumber ranges in value from 12.0 MPa to 24.1 MPa (1740 psi to 3500 psi) in compression and 8.62 MPa to 24.1 MPa (1250 psi to 3500 psi) in tension. An important difference between these two types of materials is that they reach their ultimate strength at very different strains, as discussed below.

Modulus of Elasticity

One important distinction that can be made between plastic and wood is that the modulus of elasticity (stiffness) of plastic lumber is considerably lower than that of wood. The modulus of elasticity of wood averages at 8270 MPa (1200 ksi), with Douglas fir-larch at 11720 MPa (1700 ksi). The modulus of elasticity of plastic lumber ranges from 410 MPa to 1240 MPa (60 ksi to 180 ksi) with an average of about 900 MPa (130 ksi). Through the addition of glass fibers, at least one manufacturer has increased the modulus (as measured flexurally) of their plastic lumber product to 3100 MPa (450 ksi). Even with the added reinforcement, the modulus is still appreciably lower than for wood materials.

Strain

Another important distinction that can be made between plastic and wood is that wood fractures at a much smaller strain than plastic. Essentially all types of wood typically fracture at a strain of approximately 0.7 percent, as measured in flexure. The plastic typically used in lumber (HDPE) can withstand a strain of 600–800 percent before fracture of the specimen. This large strain-to-fracture ratio is typical of samples free of stress risers or serious degradation, either one of which can decrease strain to fracture.

Creep/Time-Temperature Dependance

A serious concern when using plastic for any load-bearing application is creep. Creep is exhibited when a material has a strain that varies as a function of time when a sustained load is imposed. Due to the viscoelastic properties of plastics, a piece of plastic lumber will begin to sag over time under a static load. The time-dependent effect increases with elevated temperature. This phenomenon occurs with wood as well, but it is much less pronounced in wood that has not degraded. Civil engineers study this time-dependent phenomenon and develop load-duration factors for design use. This effect is crucial to take into account in developing design guidelines for plastic lumber.

Conventional Wood Designs

Conventional wood structures consist primarily of columns and beams. A column typically has fairly constant stress across the section. Wood and plastic in a column behave similarly assuming that each material has proper and adequate lateral bracing. On the other hand, a beam is a flexural member in which there is normally an uneven distribution of stress, plus a small shear stress (which is disregarded for current purposes), and larger stresses due to a bending moment. The stress due to the contribution of the bending moment generally will be in the form of compression near the top and tension near the bottom, with zero stress at the neutral axis lying on a plane (Figure 34a and 34b). A beam is satisfactory when fabricated from a material that has a high strength and a reasonably high modulus of elasticity. Plastic, however, does not have a high modulus and would, therefore, excessively deflect if used in a conventional type of wood design without allowances for material property differences.

In conventional wood-type designs, the typical method of accounting for the lower modulus of plastic lumber is to adjust support spans for elements used in flexure. Plastic lumber designs that have lasted for up to 8 years in field installations typically use design stresses ranging from 0.344 to 1.72 Mpa (50 to 250 psi), depending on the specific materials used. These designs are considered to be deflection-controlled, not strength-controlled.

Limitations

The three main limitations to the designer planning a structural application of plastic lumber are the material's lower modulus, creep, and its coefficient of thermal expansion, which is higher than wood. The first two issues can be dealt

with in most instances by specifying a stiffened product or change in the design of supports and spans.

Thermal expansion coefficients for plastic lumber are on the order of 1.3 E -4 to 6.3 E -5 per degree C (7.4 E -5 to 3.5 E -5 per degree F), which is between one to two orders of magnitude above wood. (On the other hand, wood's dimensions are much more sensitive to water.)

A number of ways have been devised to deal with thermal expansion in plastic lumber. The simplest technique involves reducing thermal stresses by designing a freestanding all-plastic structure. When this is not possible, special fastening can be used to allow some freedom of motion. For example, decking clip systems may be used to allow plastic decking freedom of motion at the edges.

Cost

The board-foot cost of plastic lumber is typically 25–50 percent or higher than that of pressure treated lumber of the same size. This factor alone would make the cost of a plastic lumber structure higher than a similarly designed treated wood structure. The higher cost of plastic is further exacerbated by the fact that, due to the lower stiffness of plastic, a closer spacing of support elements is required. Increasing the number of structural elements raises the materials and installation costs for a plastic lumber structure. Therefore, simply altering the inherent qualities of plastic so it can be utilized in a typical wood design may not the best approach to obtaining an efficient and economical structural design with plastic. However, there are many applications where the extremely low rate of plastic lumber degradation (provided it does not contain a large fraction of wood filler) can be used to justify use based on total life-cycle costs.

Innovative Arch Design

Concept Description

Instead of trying to use plastic lumber as a substitute for wood in conventional structures, a better approach would be to use plastic lumber in applications that take advantage of plastic's inherent mechanical properties (e.g., their low stiffness and high elongation to failure. This approach could produce structures that have a lower installed cost while taking advantage of benefits such as high longevity and environmental friendliness.

A structural arch made with a standard piece of plastic lumber can take advantage of plastic's high compressive strength and its ability to withstand high strain without failure (provided that stress risers are below a critical value). An arch is a much more efficient structural form than a flexural member, and one that carries almost pure compression. Under varied loading conditions, bending will be introduced, but the predominant state of stress is compression. Stress is not zero anywhere in such structures, and more importantly, it is considerably lower than in similarly spanned and similarly loaded flexural members (Figures 35a and 35b).

Plastic lumber can be made into an arch either by taking advantage of its creep properties or by molding the lumber into an arch shape. The fact that there is no location within the structure where the stress is zero makes this a more efficient design methodology. For example, a 890 N (200 lb) force centered on a nominal 2x4 spanning 0.61 m (2 ft) creates a maximum stress at the top and bottom surfaces of 6.30 MPa (920 psi), with the stress being zero along a plane in the geometric center. The same force on a nominal 2x4 spanning 2.44 m (8 feet) creates a maximum stress at the top and bottom surfaces of 22.1 MPa (3200 psi). The maximum stress created by a 890 N (200 lb) force on a 2x4 spanning 2.44 m (8 ft) with a 20 degree bow is reduced to 0.69 MPa (100 psi), and is not zero anywhere in the section.

This concept was first developed and demonstrated by the Center for Plastics Recycling Research at Rutgers University. A bridge frame with a 9.75 m (32 ft) free span was designed and formed by bending four 6x8 sections of plastic lumber into an arch. The plastic lumber was jacked into the arch form while being supported in the center. The arch was designed for a distributed load of 107,000 N (24,000 lb), equivalent to the width of 120–150 people. The series of arches could be used as the substructure of a bridge.

Figure 36 shows the series of arch members fabricated to demonstrate this design concept. Working with the New York City Department of General Services, these arches were for a bridge that was to become a part of the Tiffany Street Pier. Figure 37 is a schematic of the design. During the construction of the demonstration arches, however, a problem developed approximately 1 month after fabrication. In this demonstration, straight plastic lumber members were forced into arch shapes at typical outdoor summertime temperatures. Cracks formed on top of two of the four arches (Figure 38). It was determined that the problem was caused by the addition of short-strand fiberglass intended to increase the stiffness of the plastic. The fibers, while increasing the stiffness, also reduced the allowable strain before fracture. Also, pockets of unwetted fiberglass were found at the fracture locations (Figure 39). The unwetted fibers not only acted as voids (stress risers), but also caused inefficient stress transfer within the material. The voids and inefficient

transfer amplified stresses in the plastic immediately adjacent to these areas, which then initiated cracking.

It may have been an error to use plastic lumber that contained fiberglass additives for stiffening. A plastic lumber product that does not contain such stiffening additives would probably relax more easily (creep) to accept the applied strain without cracking. Also the fiberglass-stiffened plastic lumber might have performed well had it been formed into an arch at polymer processing temperatures. However, this potential solution would drive up costs of handling and shipping, and it would permit less adaptability in the field, where last-minute adaptations may be advisable to compensate for unanticipated site conditions.

Another possible factor in the cracking was the method of stress application used to bend the plastic lumber into the arch form. The arch was bent using two closely spaced support points, which created a kink in the structure. The apex of the arch ended up being the only part of the member in bending, which concentrated the strain. Two of the four arches eventually relaxed to form a smooth arch. The two arches with the large defects near the apex did not have an opportunity to relax before critical cracking occurred. In future constructions, the distribution of applied stress should be more uniform, allowing the whole member to bend into an arch. A second attempt at forming arches could not be made due to a lack of resources.

Cost Benefits and Comparisons

Two designs were developed as a comparison for bridge construction with the same construction performance parameters—a 32-ft free span, 7-ft wide, with a distributed load of 24,000 pounds. One of the bridge designs was the least expensive choice for wood (a glue-lam design), while the other was a plastic lumber arch. In both cases, conservative estimates for maximum stress levels for each material, taking into account the properties in that material, were used. A plastic lumber bridge using traditional heavy timber designs was not considered, as it was already known that such a design would use far more material and construction time and effort than either of the other two designs, and would thus be the most expensive to build. The estimated materials cost for the plastic lumber arch-type bridge was between $4,000 and $5,000. The estimated materials cost for pressure-treated, glue-laminated timber was between $6,200 and $6,700. Neither of these estimates include labor or equipment required to build the installation, but it is considered a reasonable assumption that these costs would be comparable in either case. This construction example represents the first where plastic lumber can be used in a loadbearing application with a comparable installation cost to wood. The longer life and lower maintenance expected from a plastic lumber design translates to the

promise of a much lower life-cycle cost for these materials. It should be noted, however, that this observation was for particular performance requirements, and the advantage for plastic lumber is not expected in all types of applications. Further, this industry is a long way from standard design guidelines for this type of arch construction. This example represents, however, the potential for the plastic lumber materials.

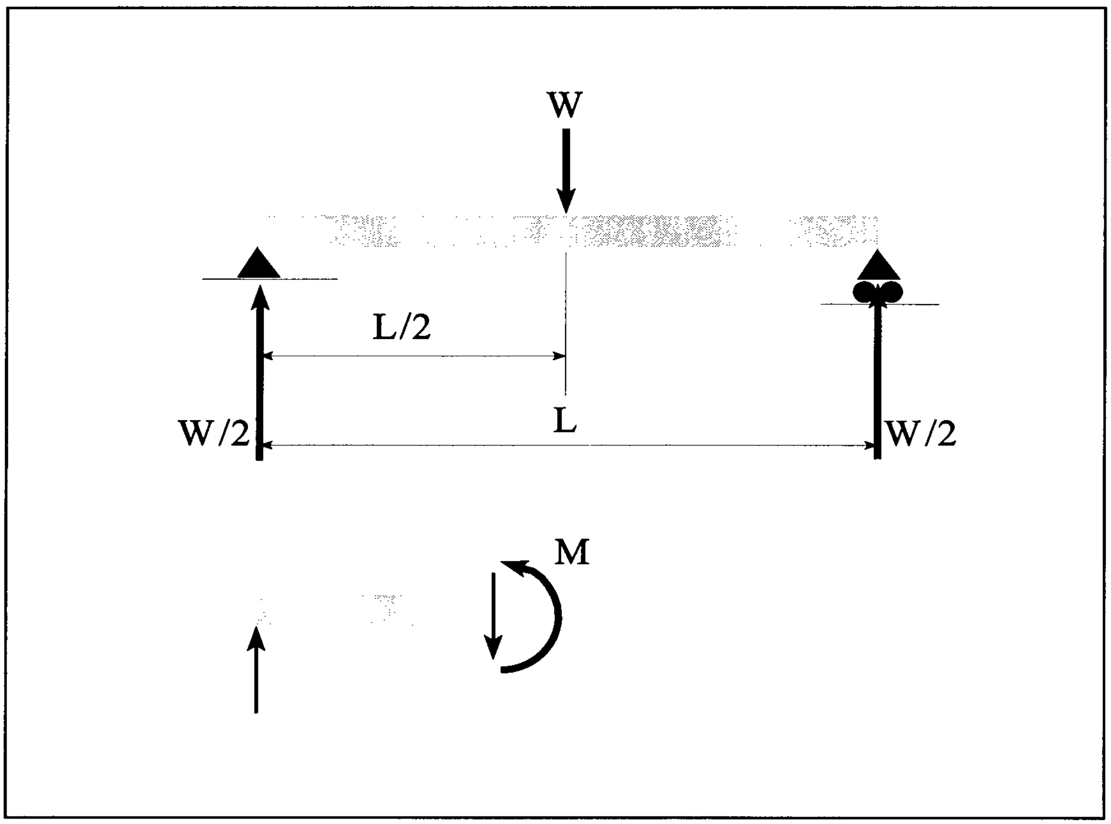

Figure 34a. Free body diagram for a beam.

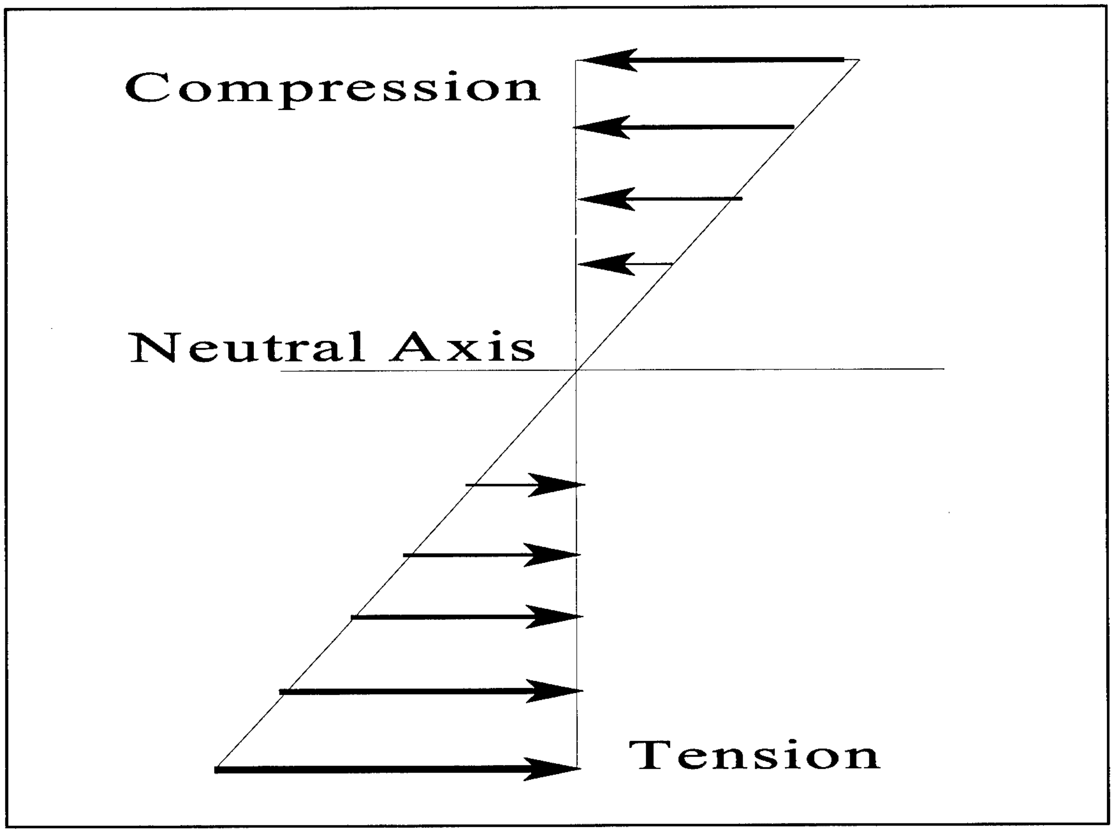

Figure 34b. Stress distribution for a beam.

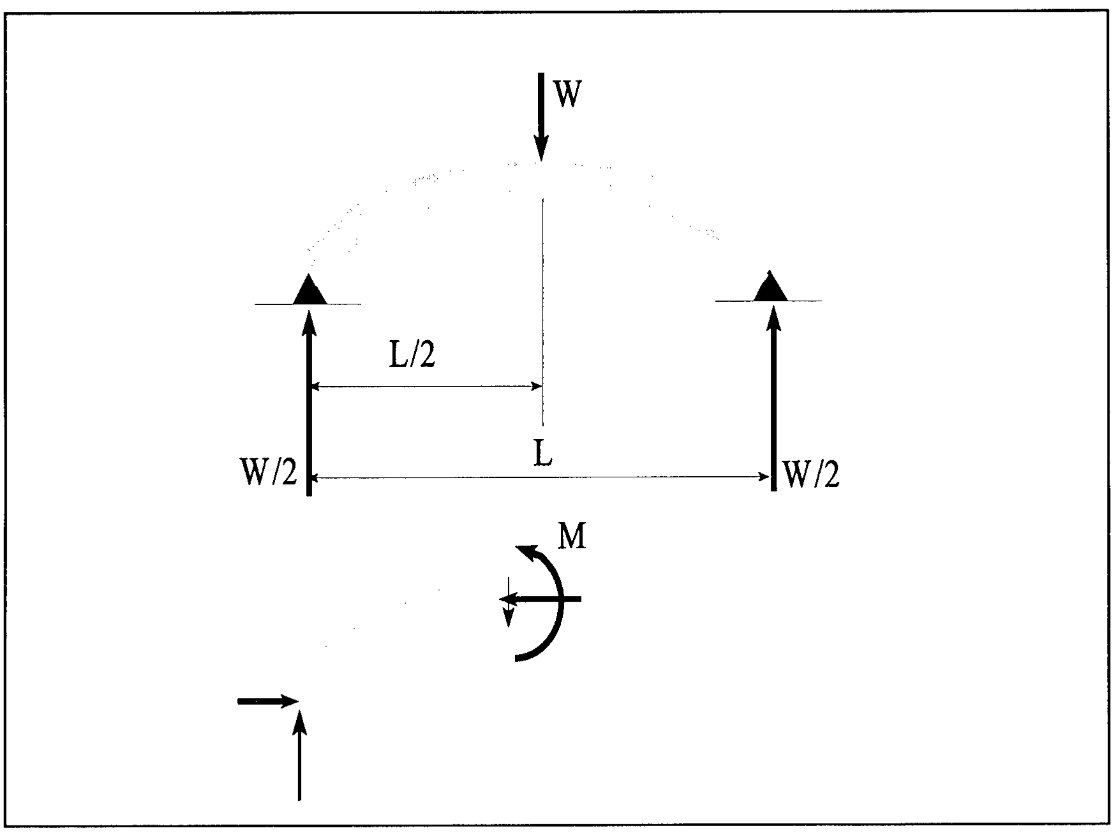

Figure 35a. Free body diagram for an arch.

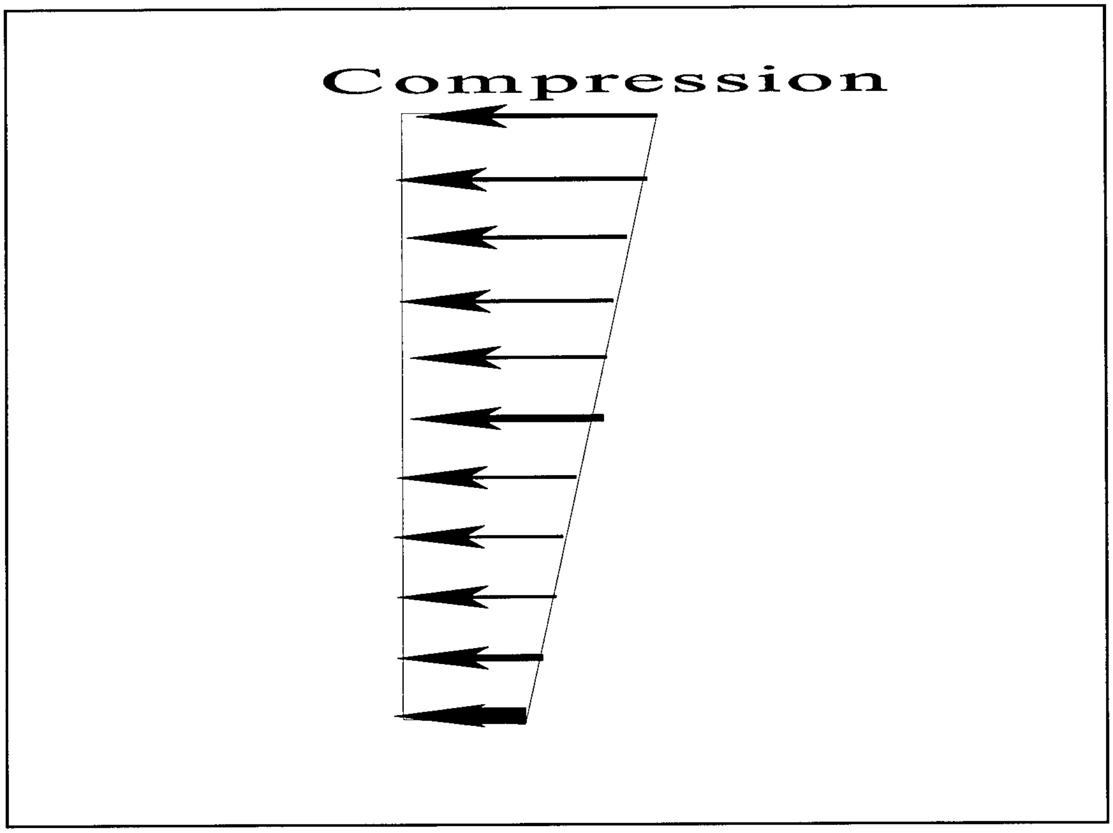

Figure 35b. Stress distribution for an arch.

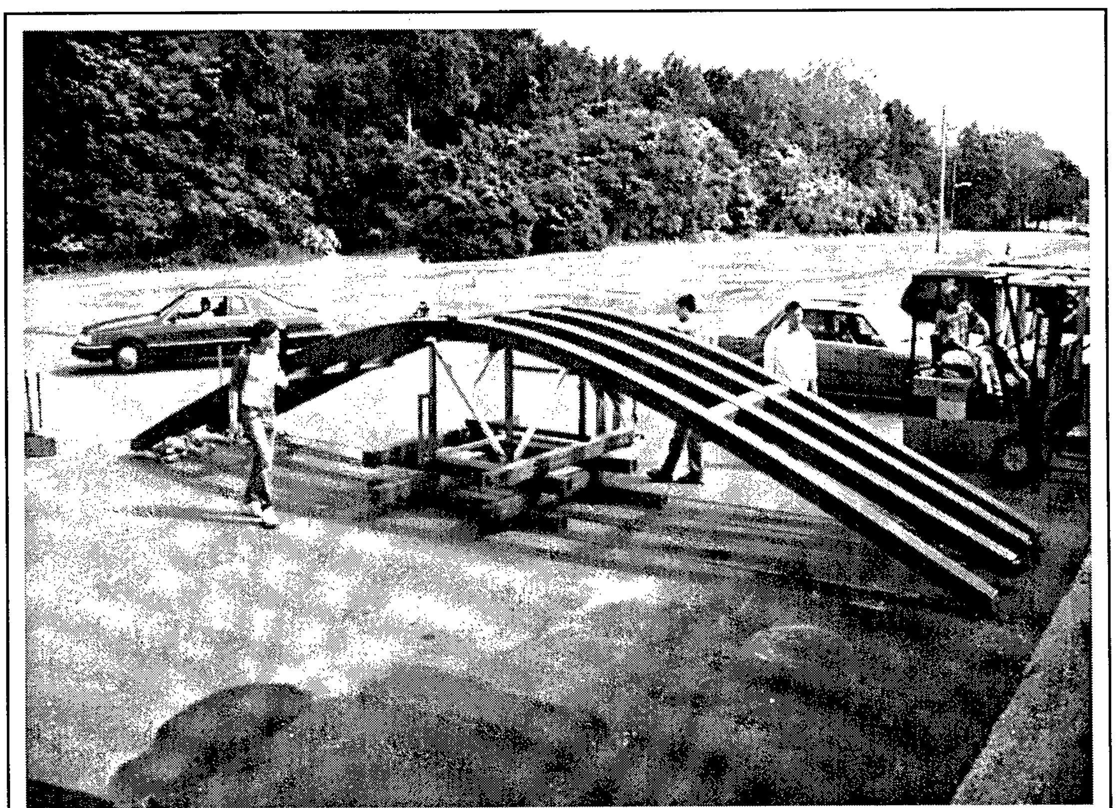

Figure 36. Plastic lumber being formed into structural arches.

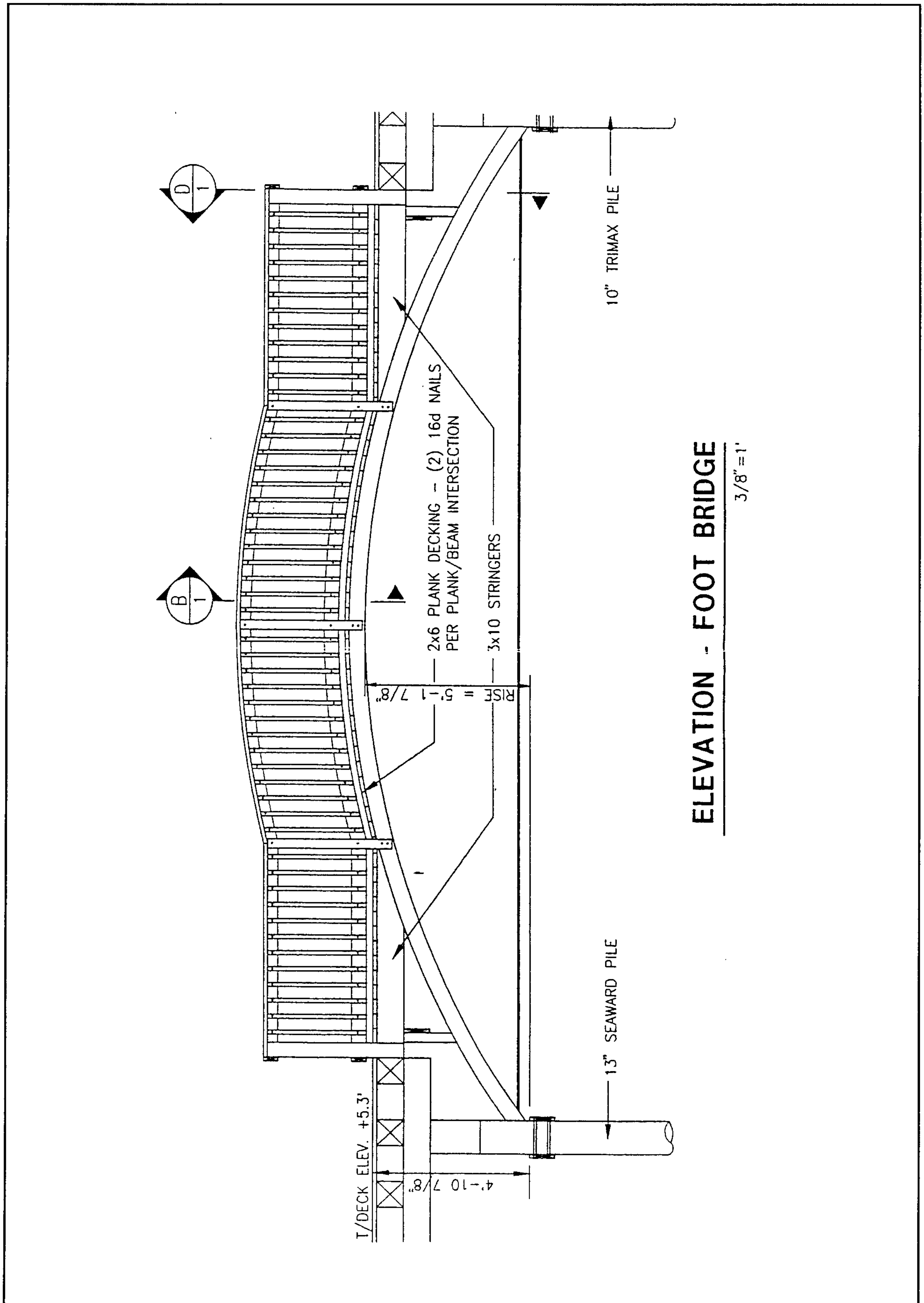

Figure 37. Schematic drawing of proposed arch bridge to be installed at the Tiffany Street Pier.

Figure 38. Cracking of the arch as viewed from the side.

Figure 39. End view of cracked arch section showing stress riser of unwetted fiberglass.

6 Demonstration Constructions

General

It was originally planned to use each participating manufacturer's materials, in various demonstration facilities. However, receiving the products and completing the laboratory mechanical property evaluations took considerably longer than originally planned. The testing delays, in turn, delayed the design and coordination of the demonstrations. Project time and resource constraints ultimately prohibited completion of the planned constructions. This chapter summarizes the status of each demonstration, whether completed or not. The construction of the Tiffany Street Pier in New York City is also reviewed in this Chapter. Although the pier was not specified in the CPAR-CRDA, its design and construction was significantly impacted by technology transfer from the CPAR project.

Lake Shelbyville, IL

At Lake Shelbyville, IL, a Corps-managed water conservation and recreational site, two particular types of wooden structures need to be replaced every year or two: a floating goose nest and a wildlife observation shelter. The floating goose nest is continuously in the water while the observation shelter gets partially submerged during heavy rains and high water.

Floating Goose Nest

The floating goose nest is basically a raft on which a galvanized steel tub is mounted. (The geese build their nest in the tub.) The demonstration raft was constructed from 2x4 and 4x4 plastic lumber materials remaining after the completion of the mechanical property tests. Before delivery to the site, the raft was test floated. This test showed that there was not sufficient buoyancy; the top surface of the raft was just barely out of the water. (HDPE has a specific gravity of approximately 0.96.) To compensate for the lack of buoyancy, the cavity under the raft was filled with urethane foam.

Wildlife Observation Shelter

The observation shelter was designed using 2x4s and 4x4s for the main framing, and tongue and groove 1x6s for the siding and roofing. Construction of the shelter was not completed before the demonstration phase of the project closed. Arrangements are being pursued with Lake Shelbyville personnel to complete this shelter outside of the CPAR program.

Boardwalk at Canaveral Locks, FL

Plastic lumber was demonstrated on a 1700 x 3 ft boardwalk at the Canaveral Locks, Port Canaveral, FL. The wooden boardwalk, which provides access along the entire lock facility, was slated for replacement.

Arrangements were made with each participating manufacturer to supply 2x4 plastic lumber for decking. Each manufacturer's material was used in a section about 12 ft in length along the boardwalk (Figures 40 and 41). Except for these plastic lumber demonstration sections, the rest of the structure was replaced with treated wood. Where the plastic lumber decking was used, the joists were spaced 12 in. on center, as opposed to the 16 in. centers used for the wood decking.

Approximately 9 months after completion of the replacement boardwalk, CPAR Principal Investigators personally inspected the condition of the plastic lumber decking sections. No visual deterioration was observed. In cooperation with the Army Engineer District, Jacksonville, site personnel perform periodic inspections of the decking boards, and no deterioration or obvious changes in the plastic lumber decking have been observed. However, Jacksonville personnel have noticed and commented on the greater deflections that occur in the plastic lumber—especially in boards that have a hollow cross-section. No cracking or other failures have occurred in these boards, however.

New York City Demonstrations

Tiffany Street Pier, NY

In a separate initiative to demonstrate the useful applications of materials made from recycled wastes, the New York City Department of General Services (NYCDGS) designed and constructed a 450 x 49 ft recreational pier made almost entirely from recycled plastics. This pier is located at the end of Tiffany Street in the Bronx, New

York City. This new pier replaced a conventional wooden structure that had deteriorated to the point of being unsafe. Figure 42 is a schematic showing the basic layout of the pier. Figures 43 and 44 show the pier and the structural trusses for the gazebo roof.

Although the Tiffany Street Pier was not part of the CPAR-CRDA, mechanical property information and design considerations developed as part of the CPAR project were shared with NYCDGS personnel. In return, NYCDGS personnel have shared lessons learned during pier construction and use. The established relationship continues to be mutually beneficial in terms of technology transfer. (In cooperation with the NYCDGS, two different plastic composite fender piles, being developed as part of a separate CPAR project on composite piling systems, were also installed at the Tiffany Street Pier.)

Pier Fire

On 3 August 1996, during a severe thunderstorm, lightning struck the gazebo and pier deck multiple times and set the pier on fire. Firefighters arrived quickly and extinguished the blaze. Figures 45 and 46 show the condition of the gazebo and deck after the fire. It is interesting to note that where the decking boards overlap the heavy 10 x 10 ft plastic lumber joists, most of the board remains (Figure 46). The joists are charred on the surface but, after cutting into them, it appears that they are otherwise unaffected. NYCDGS has begun action to rebuild the pier including the installation of lightning rods. Sections of the joists have been removed for laboratory testing to determine the retention of mechanical properties.

The fire and property destruction were bad news for the residents of a congested urban neighborhood with few recreational facilities. However, the pier fire has provided valuable real-world experience with plastic lumber that could not have been gained any other way. Of particular interest to project personnel and researchers is the comparative performance of the plastic pier with a conventional wooden one in case of lightning strikes. Study of the lessons learned is ongoing outside of this CPAR project.

The Tiffany Street Pier fire emphasizes the need to address fire performance issues in the ASTM plastic lumber standards currently in development.

Arch Design Bridge

As described in Chapter 5, an innovative arch design was developed as part of this CPAR project. NYCDGS personnel agreed to provide a location on the Tiffany Street

Pier, midway along the two walkways leading from the shore (see Figure 42), to construct a plastic lumber bridge using an arch design structural support. Figure 37 shows the basic design details as developed by M.G. McLaren, P.C., Consulting Engineers. As shown in Figure 38 and noted in Chapter 5, however, two of the four plastic lumber arches fabricated for the main bridge supports developed major cracks near the apex (Lampo et al., May 1996). Remaining project funds were not sufficient to pay for the fabrication of new arches. Consequently, the construction of the arch design bridge was abandoned as part of this CPAR project. The authors still believe that innovative arch designs could promote the application of plastic lumber in construction, and it is hoped that funding will be acquired to complete this bridge at Tiffany Street Pier.

Conventional Design Footbridge, Champaign, IL

To demonstrate the benefits of plastic lumber in structural applications using more conventional wood designs, construction of a footbridge structure was planned. Preliminary designs were developed and shown to a Park District in Champaign, IL. It was proposed that the plastic lumber design be substituted to replace a wooden footbridge that previously had been removed due to its poor condition. The proposed plastic lumber footbridge, illustrated in Figures 47 and 48, is approximately 34 ft long by 6 ft wide. This conventional footbridge was to be the showcase demonstration of this CPAR project.

A local engineering firm, Daily and Associates (Champaign, IL), was contracted to verify the design concepts, assist in developing the construction details, and develop the foundation requirements and details based on actual site conditions. (See Appendix A for overall design considerations.) All of the required plastic lumber materials (which included 2 x 4s, 2 x 12s, and 6 x 6s) were received. Tests to verify critical connections were initiated.

After almost one and a half years work developing the design and coordinating the construction of the bridge with Park District personnel, the project was halted over liability issues. Park District legal counsel recommended against accepting the cooperative agreement between USACERL and the Park District due to the terms of an indemnification clause related to transfer of the finished bridge from USACERL responsibility to the Park District. As of this writing, the issue has not been resolved. Other nearby sites are now being considered and funds outside of CPAR are being sought to complete this demonstration footbridge.

Lessons Learned

Feedback from the craftsmen working on the various projects provided additional insights into the behavior of the plastic lumber products. For example, stainless steel screws with the power drive head are preferred to other fasteners for their ease of installations and long-term corrosion resistance.

While the initial attempt to fabricate load-bearing arches failed, the failure modes shown in the plastic lumber has provided clues on how to successfully fabricate them next time. Although external circumstances intervened to prevent completion of the demonstrations under CPAR, the principal investigators consider the two footbridges to be excellent candidates for completion under separate funding.

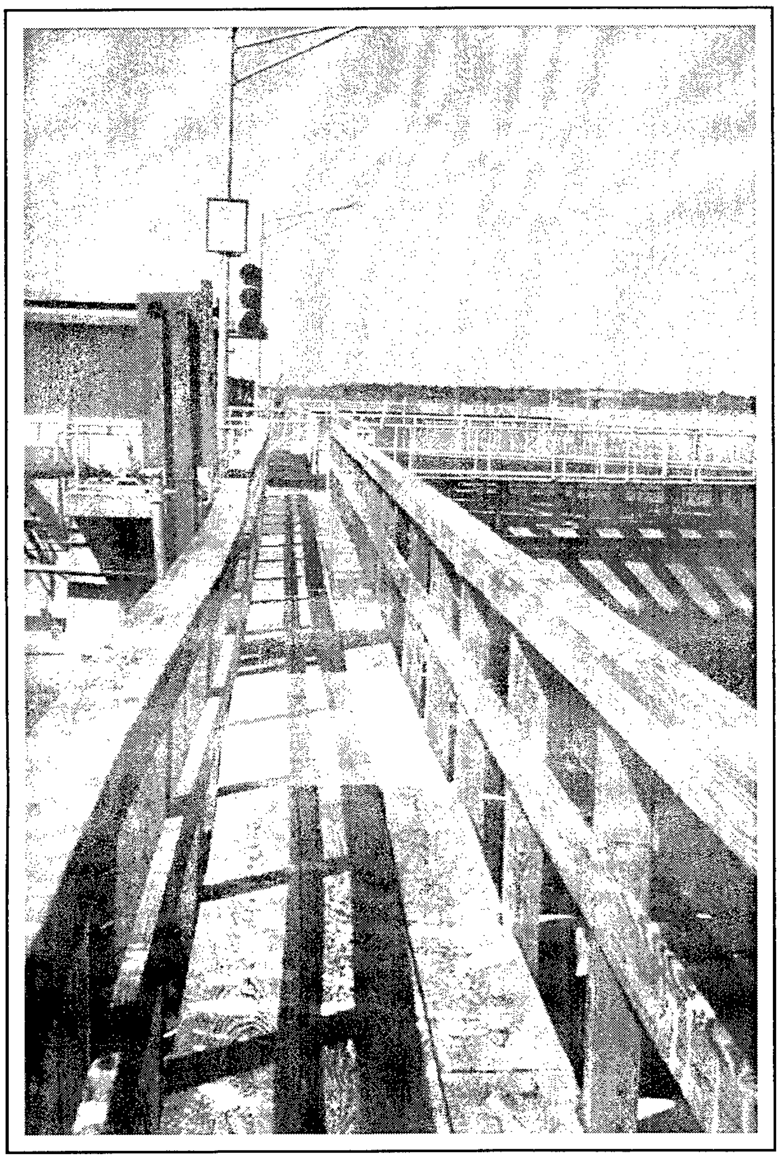

Figure 40. Boardwalk at Canaveral Lock, FL.

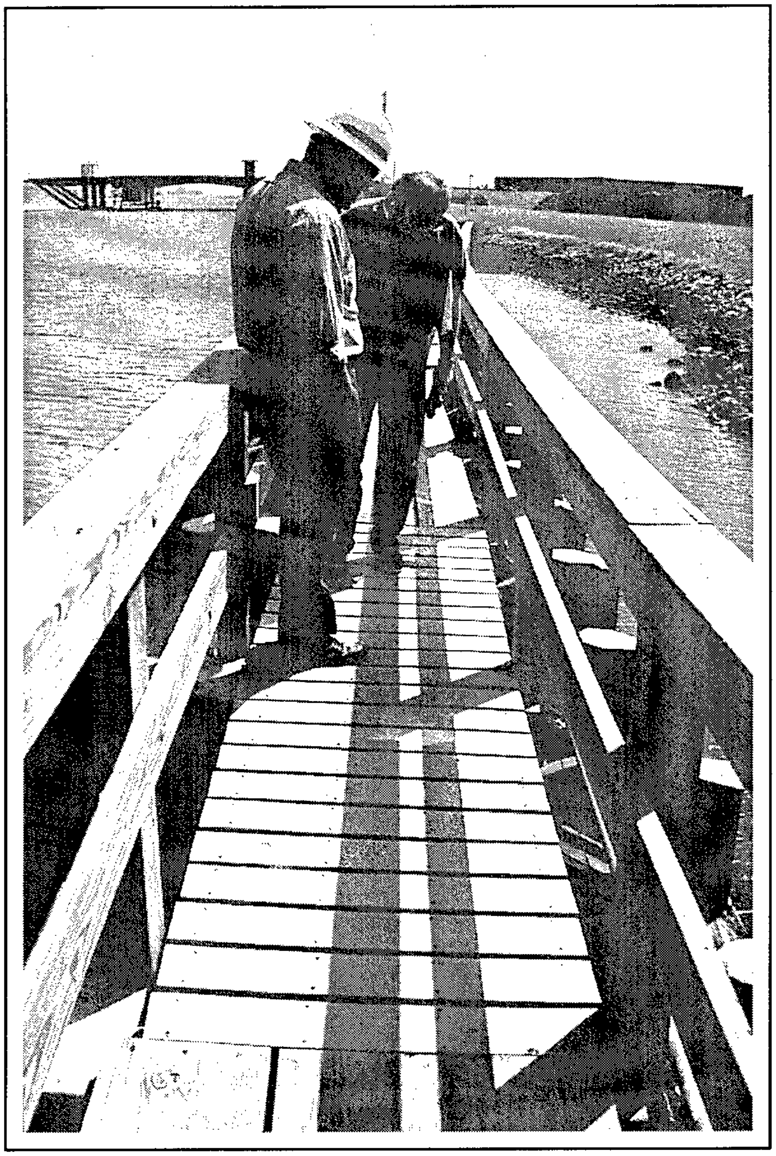

Figure 41. Inspection of plastic lumber decking installed on boardwalk at Canaveral Lock FL.

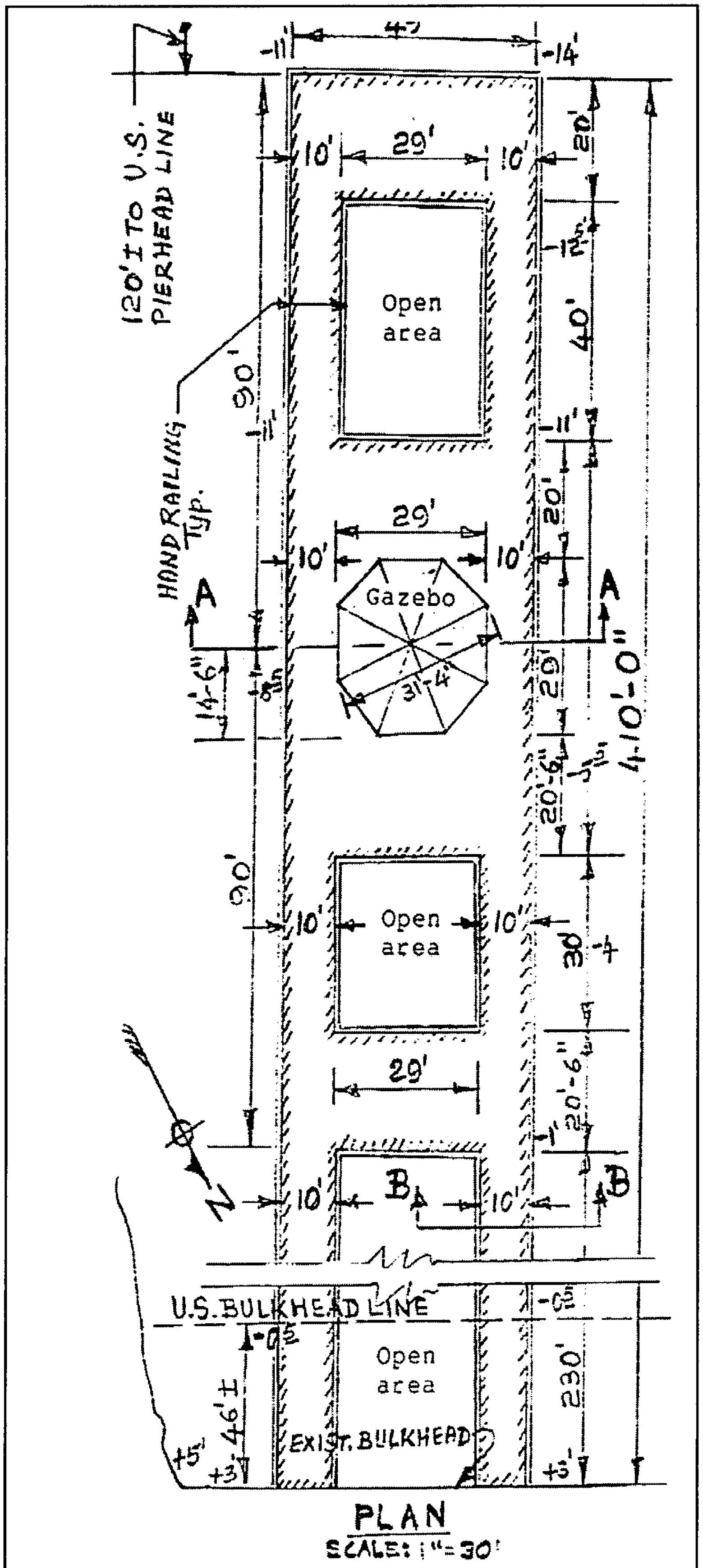

Figure 42. Schematic drawing of Tiffany Street Pier.

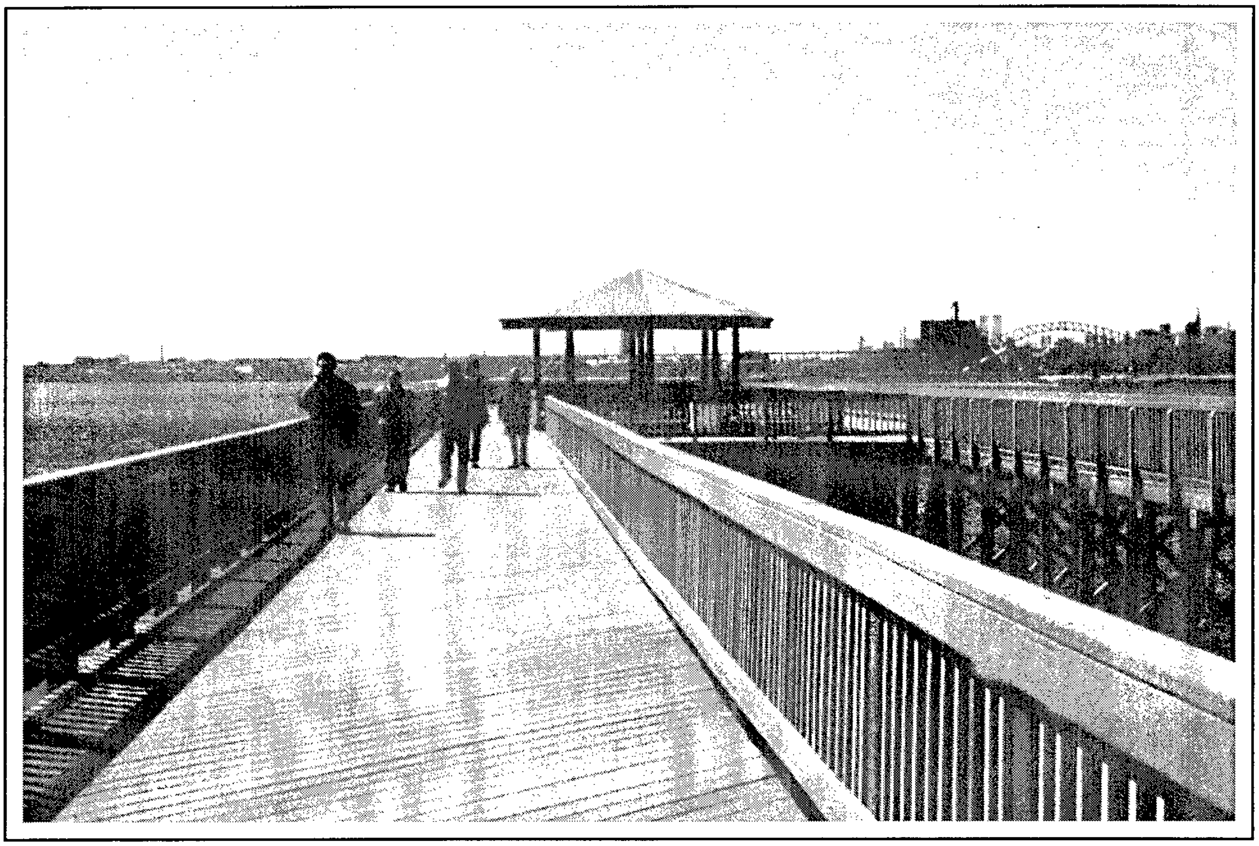

Figure 43. Tiffany Street Pier made from plastic lumber materials.

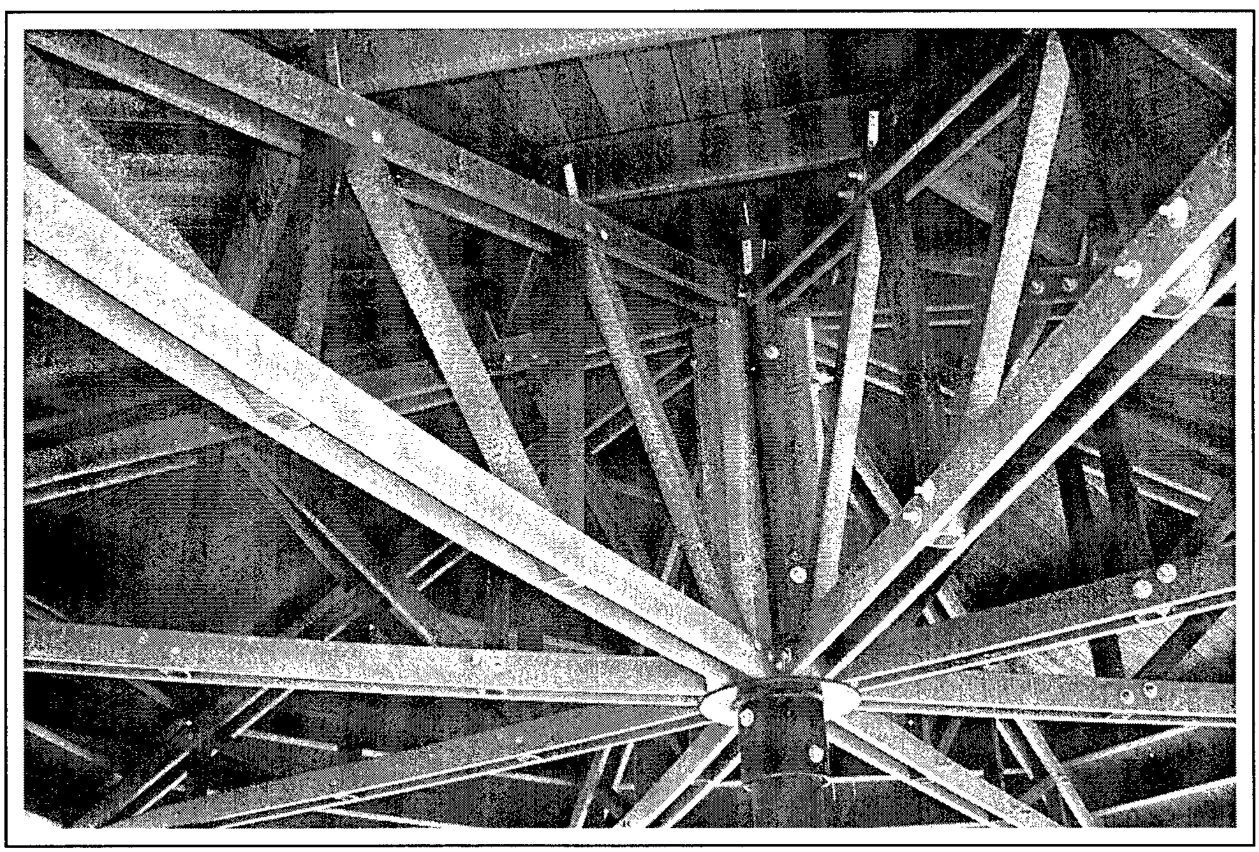

Figure 44. Structural trusses for the gazebo roof at Tiffany Street Pier.

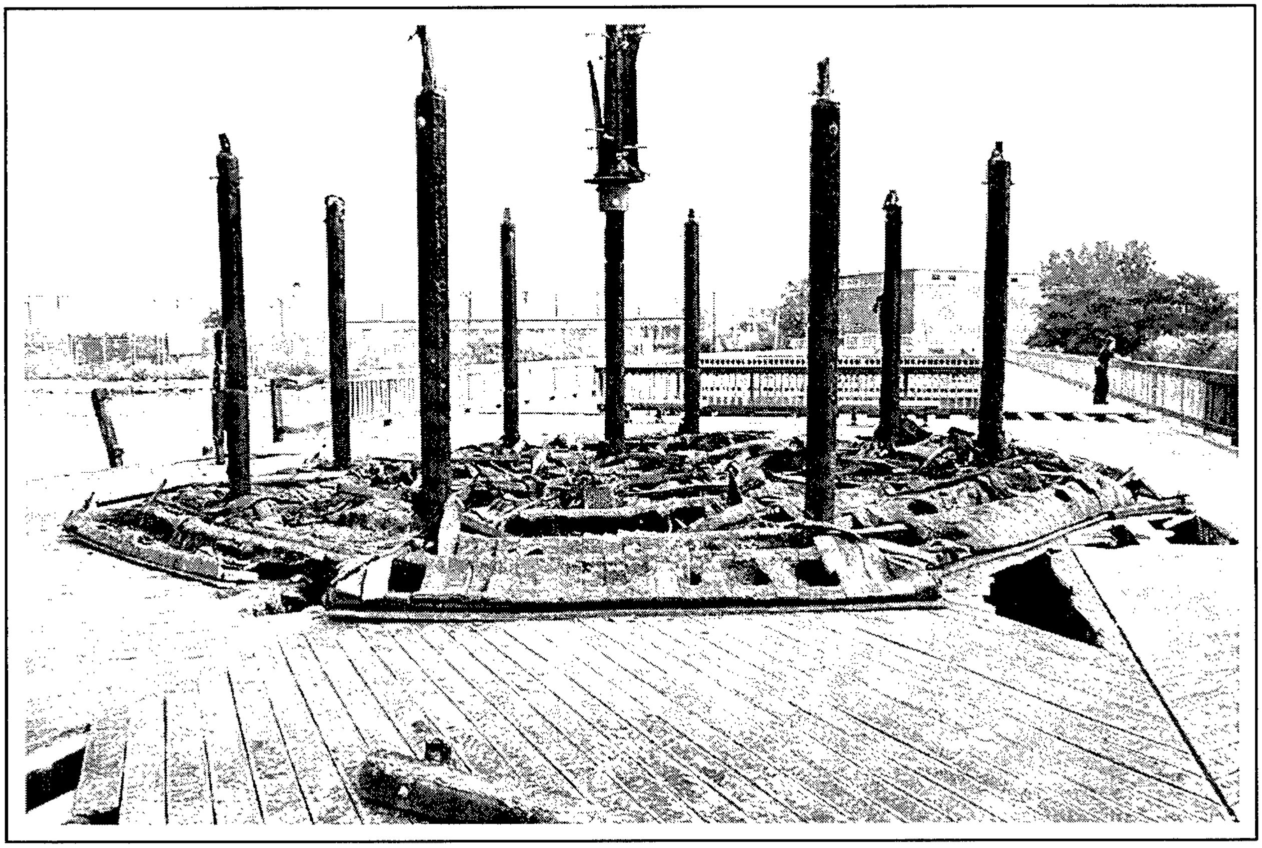

Figure 45. Remains of the gazebo after the fire.

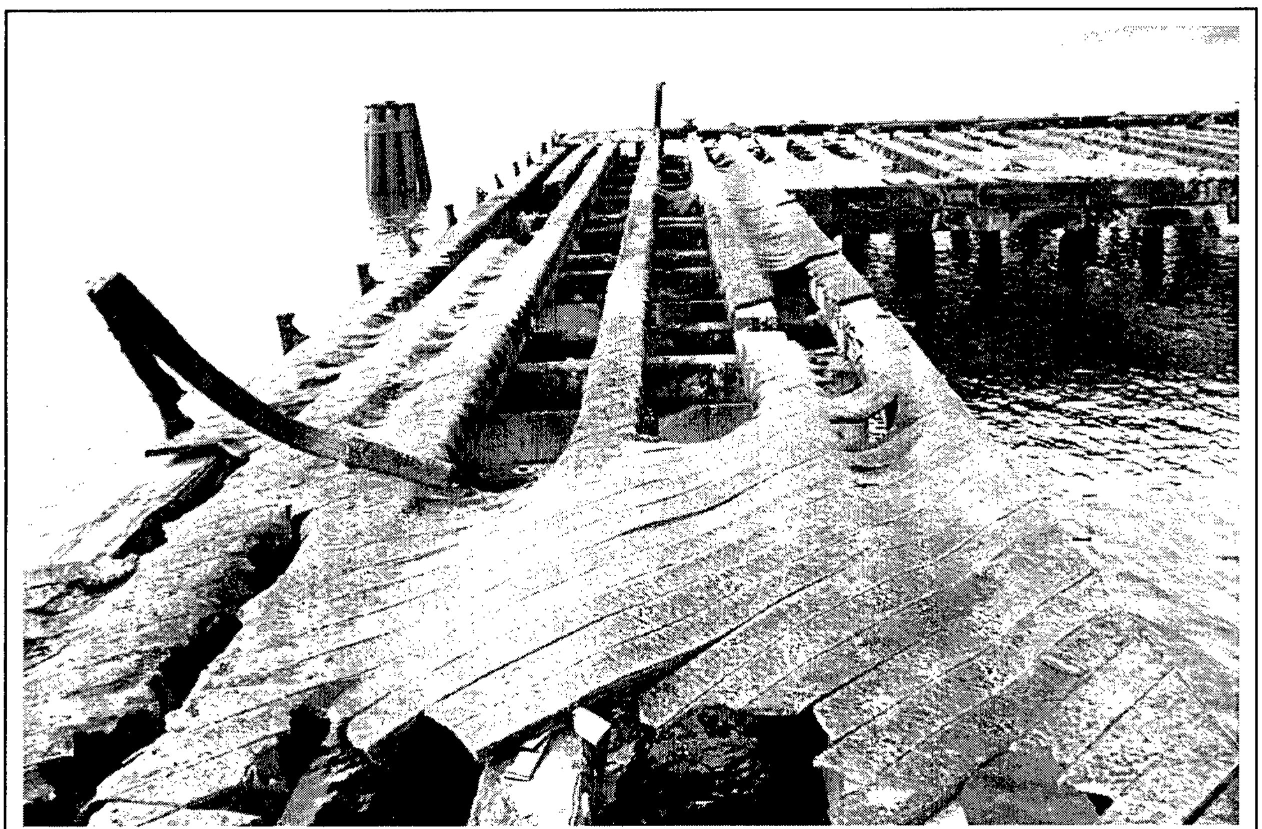

Figure 46. Fire damage to the far end of the pier. The guard rails were completely destroyed.

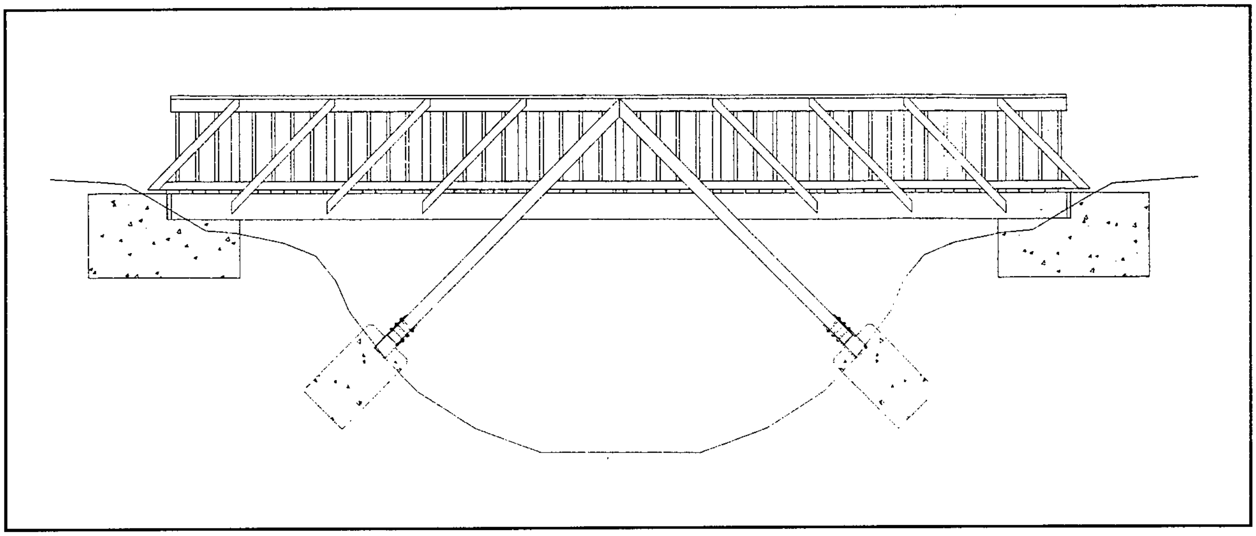

Figure 47. Elevation drawing of the proposed Park District bridge.

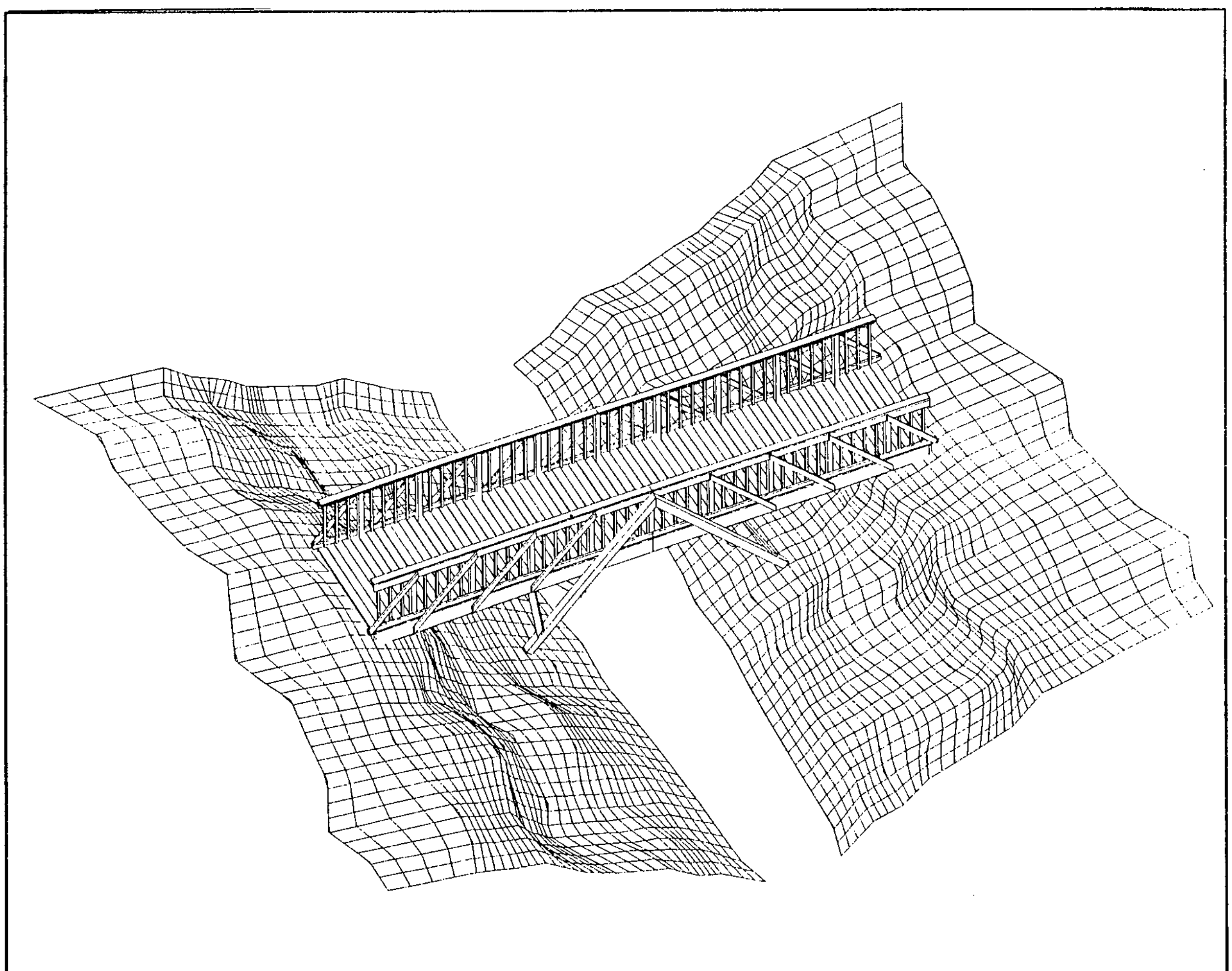

Figure 48. Schematic showing bridge in place.

7 Conclusions, Recommendations, and Commercialization

Conclusions

Based on the laboratory tests conducted as part of this CPAR project, it is concluded that mcst key mechanical properties of plastic lumber currently on the market are substantially different than the properties of similarly sized wood lumber:

- the compressive strength properties of the plastic lumber tested were equal or superior to those of wood
- plastic lumber has a modulus of elasticity (stiffness) at least an order of maginute lower than even the softest woods
- plastic lumber is subject to much higher levels of creep than wood.

Based on these findings, it is further concluded that plastic lumber products must be carefully specified by the designer or engineer when used in any load-bearing application as a replacement for wood.

When using plastic lumber in *conventional wood designs*, the designer must compensate for plastic's deflection and creep properties by specifying larger cross-sections or more closely spaced support elements (i.e., joists and columns). These modifications will in turn affect the initial cost of the structure. It is concluded that the higher initial material cost of plastic lumber may be justifiable in environments that are highly damaging to wood, such as waterfront exposures; the added durability of plastic lumber may cut the structure's total life-cycle cost when the maintenance, repair, and replacement costs of wood are taken into account. Also, depending on the objectives of the owner of the structure, the diversion of commingled plastics from the landfill may be considered an economic benefit of plastic lumber over wood. Based on first costs only, however, natural wood is less expensive for conventional designs than plastic lumber.

Plastic lumber may more optimally be applied in *specialized wood designs* that use plastic's unique material properties to advantage over wood. Preliminary work on arch design concepts, which take advantage of the plastic's compressive properties,

indicates that such structures may be built at costs equal to or lower than they could with wood. When life-cycle costs and environmental benefits are factored in, plastic lumber becomes an attractive economic alternative to costly structures such as glued-laminate wooden arches.

It is concluded that the development of accepted industry standards and test methods for plastic lumber is technically feasible. The current research has produced five new test methods now in balloting at ASTM for adoption as industry standards (see "Technology Transfer and Commercialization" below). Acceptance of these and related ASTM standards and test methods should increase market acceptance of plastic lumber and provide greater materials-specification options for the construction industry.

Recommendations

Keeping in mind the various issues presented in the conclusions above, the use of plastic lumber should be given consideration for use as a substitute for dimensional lumber and timber especially for applications in damp, wet and/or insect infested environments. The following actions are also recommended:

- It is recommended that the CPAR Partners coordinate efforts to successfully complete field demonstrations of the conventional footbridge and the arch-supported footbridge, both of which were delayed by factors not under the control of the Principal Investigators.

- It is recommended that the CPAR Partners and Partner Participants coordinate through various industry organizations and related professional societies to promote the development and acceptance of industry standards and test methods for plastic lumber materials.

- It is recommended that the CPAR Partners and Partner Participants seek new opportunities to demonstrate the use of plastic lumber in accordance with their own organizational missions, charters, and objectives. Lessons learned should be documented in papers and presentations to professional societies, and relevant data should feed into continuing efforts to set and refine industry standards for plastic lumber.

- It is recommended that the CPAR Partners consider additional investigations to identify specialized designs and applications that exploit the unique

properties of plastic lumber more effectively and at lower cost than natural wood could be used.

- It is recommended that, as the proposed ASTM specifications and standards are developed, established, and accepted by the construction industry, plastic lumber materials should be included in applicable Corps of Engineers Military and Civil Works guide specifications.

Technology Transfer and Commercialization

Through the efforts of the CPAR Principal Investigators and others, the American Society for Testing and Materials has established ASTM Section D20.20.01, "Plastic Lumber and Shapes," under Committee D20 on Plastics. This Section meets three times a year along with Committee D20. Task groups were formed to address Test Methods, Terminology, Performance Specifications, and Combustibility. The Plastic Lumber Trade Association now coordinates its business and technical meetings with these ASTM committee meetings.

Part of the product of this CPAR project were five new ASTM test methods for plastic lumber materials:

- D6108, *Standard Test Method for Compressive Properties of Plastic Lumber and Shapes*
- D6109, *Standard Test Method for Flexural Properties of Unreinforced or Reinforced Plastic Lumber*
- D6111, *Standard Test Method for Bulk Density and Specific Gravity of Plastic Lumber and Shapes by Displacement*
- D6112, *Standard Test Method for Compressive and Flexural Creep and Creep Rupture of Plastic Lumber and Shapes*
- D6117, *Standard Test Method for Mechanical Fasteners in Plastic Lumber and Shapes*.

Also currently under development and in various stages of balloting are the following documents:

- a plastic lumber performance specification

- a performance specification for recycled plastic decking boards
- a test method to measure thermal expansion
- a test method for shear properties
- a standard practice for deck design.

Also, per suggestions by the CPAR Partner Principal Investigators, manufacturers of plastic lumber formed an organization—The Plastic Lumber Trade Association—to promote the use of this material by the U.S. construction industry. When this CPAR project was initiated, the plastic lumber industry was very unstable; it was not uncommon for manufacturers to be in business one day and close their doors the next. Today, partly as a result of the efforts of the Association, the plastic lumber industry is much healthier, with a projected growth rate of 40 percent annually.

Papers about this CPAR project and plastic lumber technologies have been presented at several technical conferences in the last few years by both of the CPAR project Principal Investigators (e.g., Nosker, Renfree, and Sachan, November 1995; Nosker et al., May 1993; Sachan et al., November 1994; Van Ness et al., May 1995; Lampo, Nosker, and Renfree, November 1996; Lampo, et al., November 1995; and Lampo, April 1995).

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Appendix A: Construction Productivity Advancement Research (CPAR) Program

CPAR is a cost-shared research and development (R&D) partnership between the U.S. Army Corps of Engineers (USACE) and the U.S. construction industry (e.g., contractors, equipment and material suppliers, architects, engineers, financial organizations, etc.). In addition, academic institutions, public and private foundations, nonprofit organizations, state and local governments, and other entities interested in construction productivity and competitiveness also participate in this program. CPAR was created by the Secretary of the Army to help the domestic construction industry improve productivity and regain its competitive edge nationally and internationally. This will be accomplished by enhancing USACE construction R&D programs with cost-shared industry partnerships. The objective of CPAR is to facilitate productivity-improving research, development, and application of advanced technologies through cooperative R&D programs, field demonstrations, licensing agreements, and other means of technology transfer.

The Federal Government is the largest single buyer of construction services. Technology advancements that improve construction productivity will reduce construction program costs. Projects not now economically feasible may become feasible due to lower construction costs. Such cost savings would accrue directly to the Federal Government's construction program, and would benefit the U.S. construction industry and the U.S. economy in general.

CPAR is intended to promote and assist in the advancement of ideas and technologies that will have a direct positive impact on construction productivity, project costs, and USACE mission accomplishments. R&D and technology transfer under CPAR is based on proposals received from educational institutions, the construction industry, and others that will benefit both the construction industry and the Corps of Engineers. The CPAR Program permits USACE to act on ideas received from industry, to cost-share partnership arrangements, and to rapidly implement successful research results through aggressive technology transfer and marketing actions. Section 7 of the Water Resources Development Act of 1988 (P.L. 100-676) and the Stevenson-Wydler Technology Innovation Act of 1980, as amended (15 U.S.C. 3710a *et sea.*) provide the legislative authority for the CPAR Program.

Appendix B: Bridge Design Assumptions

For the design of the Park District bridge, several assumptions regarding the loads on the bridge were made. The concentrated loads were calculated as the weight of the decking plus the weight of a riding lawn mower with driver. This totals 2100 pounds. The live load from pedestrian traffic was assumed to be 100 lb/sq ft. With these assumptions, load transfers along the interior and exterior joists were calculated as 112.05 plf and 75.63 plf, respectively. For loading, the larger of the two was taken.

Assumptions	Weight (lb)
riding lawn mower	613
driver weight	200
Total	813

Dead Loads	Area of Section (sq. in.)	weight/foot (lb/ft)	length of members (ft)
Main beams (6x6)	30.25	10.53	7.125
Long Span Joists (2x12)	17.25	6	32.7083
Decking (2x6)	8.25	2.77	7.125
Railing Posts (4x4)	12.25	4.26	4.5
Diagonals (2x4)	5.25	1.83	5.3645
Hand Rails (doubled) (2-2x6)	16.5	5.74	32.7083
Vertical Rails (2x2)	2.25	0.78	3.5
Main Supports (6x6)	30.25	10.53	12
Secondary Supports (4x4)	12.25	4.26	7.125
Total	1281 lb		

Live Loads	(lb/sq ft)
Pedestrian Load	100

Load Transfers	Influence Area per foot (width in feet)	Joist (plf)	Decking (plf)	Live Load (plf)	Total (plf)
Load along interior joists (plf) 112.05 plf	1	6.00	6.05	100.0	112.05
Load along exterior joists(plf) 75.61 plf	0.5	6.00	6.05	50.0	59.02

For loading, take the larger of the two above values: 112.05 plf (along the joists).

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Defense Nuclear Agency
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